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13. ABSTRACT *(Maximum 200 words)*

With support from AFOSR, ONR, and NSF (through CUOS), the Alaska Meeting on Fundamental Optical Processes in Semiconductors (AMFOPS) was held in Girdwood Alaska, Aug. 5-10, 2001. The meeting was highly successful (many of the attendees have informed me that this was the best conference they have attended in years). The goal of the conference was to bring together the leading international groups working in semiconductor optics in a workshop format to present the most recent exciting results, and to discuss the future directions of the field. A major emphasis was place on having a strong US presence (since most of the significant conferences in the field have been held in Europe or Asia in recent years), and almost all the active US groups were represented.

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PROCEEDINGS

for the

Alaska Meeting on Fundamental Optical Processes in Semiconductors

AMFOPS '01

The Westin Alyeska Prince Hotel
Girdwood, Alaska

August 5 – 10, 2001

ALASKA MEETING ON FUNDAMENTAL OPTICAL PROCESSES IN SEMICONDUCTORS

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AMFOPS CONFERENCE SCHEDULE

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
7:00 AM 7:15 AM 7:30 AM 8:00 AM	BREAKFAST IN PRINCE	BREAKFAST IN PRINCE	BREAKFAST IN PRINCE	BREAKFAST IN PRINCE	BREAKFAST IN PRINCE
8:15 AM	WELCOME-COLUMBIA ROOM	TALKS IN COLUMBIA ROOM	TALKS IN COLUMBIA ROOM	TALKS IN COLUMBIA ROOM	TALKS IN COLUMBIA ROOM
	Ultrafast Dynamics! - Lu Sham	**Microcavities I - Galina Khitrova**	**Quantum Dots II - Dan Gammon**	**Quantum Information - Jag Shah**	**Quantum Dots III - Y. Arakawa**
8:30AM	MA1- Wegener-"From Quantum kinetics to the carrier-wave regime".	TuA1-Capasso-"MEMS based on Casimir forces".	WA1-Grandidier-"Structural and electronic studies of InAs quantum dots embedded in GaAs by scanning tunneling microscopy".	ThA1- - "TBA"	FA1-Molinari-"TBA"
9:00AM	MA2-Haug-"Quantum kinetics for e-h- plasmas and excitons".	TuA2-Khurgin-"Excitonic radius in the cavity polariton in the regime of very strong coupling".	WA2-Forchel-"Single and coupled quantum dot spectroscopy".	ThA2-Steel-"Quantum dots: Artificial atoms and quantum computing".	FA2-Cingolani-"Structural, optical and electrical spectroscopies of quantum dots at nanoscale".
9:30AM	MA3-Chemla-"High order correlations in semiconductors".	TuA3-Reinecke-"From semiconductor microcavities to photonic crystals".	WA3-Arakawa-"Fabrication and optical properties of quantum dots: GaN-based and InAs Quantum Dots".	ThA3-Sham-"Theory of ultrafast light manipulation of spin-excitons in nanodots for quantum computing".	FA3-Deppe-"Exciton relaxation in QD's and application to lasers and microcavity emitters".
10:00 AM	BREAK IN FOYER	BREAK IN FOYER	BREAK IN FOYER	BREAK IN FOYER	BREAK IN FOYER
	Quantum Dots I - Art Smirl	**Ultrafast Dynamics II - Daniel Chemla**	**Quantum Dots and Photonic Crystals II: Henry Van Driel**	**Microcavities II - Yoshi Yamamoto**	**Quantum Dots and Ultrafast Dynamics III - Duncan Steel**
10:30 AM	MB1-Gammon-"Spin in single quantum dot spectroscopy".	TuB1-Perakis-"Ultrafast nonlinear optical dynamics of the electron gas".	WB1-Michler-"A quantum dot single-photon emitter".	ThB1-Houdre-"Angular resolved emission of cavity-polaritons under resonant excitation".	FB1-Borri-"Ultrafast gain dynamics and dephasing times in quantum-dot amplifiers from room to cryogenic microsphere".
11:00 AM	MB2-Gershoni-"Optical spectroscopy of single quantum dots at tunable postive, neutral and negative charge states".	TuB2-Smirl-"Coherence and exciton-exciton interactions".	WB2-Scherer-"Periodic structures and efficient nanocavities for controlling spontaneous emission".	ThB2-Baumberg-"Microcavity polariton traps: What do you get if you cross light and matter"?	FB2-Wang-"Cavity QED of quantum dots with dielectric microsphere".
11:30AM	MB3-Abstreiter-"Luminescence spectroscopy on single quantum dots".	TuB3-Merlin-"The dark side of the Cerenkov effect."	WB3-O'Brien-"VCSEL pumped photonic crystal lasers".	ThB3-Ciuti-"Parametric emission of microcavity polaritons".	FB3-Takagahara-"Theory of excitonic rabi flopping, quantum interference and dephasing in single quantum dots".
12:00AM	MB4-Finley-"Charged and neutral excitons complexes in individual InGaAs quantum dots".	TuB4-Runge-"Theory of resonant secondary emission".	WB4-Krauss-"Progress towards photonic crystal integrated optics".	ThB4-Flytzanis-"Nonlinear magneto-optic microcavities".	FB4-Gonokami-"Coherent manipulation of cold biexcitons in CuCl".

PG. 1 (CONTINUED)

12:30 PM	LUNCH IN PRINCE ROOM	LUNCH TOP OF THE MOUNTAIN	LUNCH IN PRINCE ROOM	LUNCH IN PRINCE ROOM Panel Discussion: New Directions in Physics of Semiconductors.	LUNCH IN PRINCE ROOM FC1-Koon-"Polar bear optics, twenty years later; Fuzzy Wuzzy wasn't photonic, was he"?
2:00PM	**Photonic Crystals I - Axel Scherer** MC1-John-"Photonic band gap materials: A semiconductor for light".				**Ultrafast Dynamics IV - David Citrin** FC2-Cundiff-"Local field effects in a dense atomic vapor".
2:30PM	MC2-Welsbuch-"Waveguide-based 2D photonic crystals: a few building blocks towards 3D confined structures".				FC3-Sipe-"Coherent control of carriers, currents, and spin".
3:00PM	MC3-Noda-"Photonic band gap crystals and and devices".				BREAK IN FOYER
3:30PM	BREAK IN FOYER	FREE TIME	FREE TIME	FREE TIME	**Ultrafast Dynamics V - Ted Norris** FD1-Woerner-"Ultrafast coherent electron transport in GaAs/AlGaAs quantum cascade structures".
4:00 PM	POSTER SESSION IN COLUMBIA C				FD2-Thomas-"Optically induced coherent transport phenomena in semiconductor nanostructures with disorder".
4:30PM	AND FOYER (contributed papers)				FD3-Citrin-"Optical/THz properties of semiconductor quantum wells".
7:00PM	BANQUET IN PRINCE ROOM	EVENING SESSION IN COLLUMBIA ROOM **Resonant Emission & Discussion - David Citrin** TuC1-Koch-(tutorial) "Coherence, luminescence, excitons, and all that...".	EVENING SESSION IN COLLUMBIA ROOM **Photonic Crystals III & Discussion - Claude Weisbuch** WC1-VanDriel-"Tuning photonic crystals".	EVENING SESSION IN COLLUMBIA ROOM **Microcavities III & Discussion - Ronald Zimmerman** ThC1-Yamamoto-"Exciton-polariton lasers and amplifiers".	
7:30PM		TuC2-Deveaud (tutorial) "Early stages of secondary emission in quantum wells".	WC2-Slusher-"Slow, highly nonlinear propagation in waveguide-disk resonator structures".	ThC2-Astratov-"Stimulated Scattering in semiconductor microcavities".	
8:00PM		TuC3-Kira-"Microscopic theory of semiconductor luminescence and terahertz absorption".	WC3-Giessen-"Controlling the interaction between light and gold nanoparticle arrays".	ThC3-Bloch-"Spontaneous and stimulated polariton relaxation".	
8:30PM		Panel discussion of "The Physics of Luminescence"	Panel discussion "Propects for Photonic Crystals".	Panel discussion "Bosonic Effects With Excitons".	
10:00PM					

7/17/01

From Quantum Kinetics to the Carrier-Wave Regime

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Abstract:
For times shorter than the phonon [1,2] or plasmon period [3,4] (50-100 femtoseconds in the model semiconductor GaAs) these excitations look almost static and carrier scattering becomes quite unusual. Corresponding results out of this regime of quantum kinetics are briefly summarized. For yet shorter times, i.e. times shorter than the period of light (or, to be precise, the band gap period, 2.9 femtoseconds in GaAs) [5,6] we can observe new nonlinear optical phenomena such as carrier-wave Rabi flopping and the breakdown of the area-theorem. This carrier-wave regime becomes accessible by using both, extremely short (less than 5 femtoseconds) and extremely intense (Rabi periods less than 3 femtoseonds) optical pulses. Corresponding unpublished experimental [7] and theoretical results are presented. This might open the door to studies on electron dynamics on a timescale of just one or two femtoseconds.

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"Quantum kinetics for e-h-plasmas and excitons"

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Abstract not available

High order correlations in Semiconductors

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Materials Sciences Division, E. O. Lawrence Berkeley National Laboratory, Berkeley, California

(May 24, 2001)

A good recipe for finding something new is to design experiments for conditions in which it is expected that the most advanced theories are likely to be invalid. In this conference we describe two of these experiments.

The Dynamically controlled truncation scheme (DCTS) formalism has been developed for describing coherently driven *e-h* pair systems generated in the initial phase following laser excitation of the semiconductor in its ground state[1]. This approach, which includes the Semiconductor Bloch Equations[2], has been very successful in explaining 2-particle[3] and 4-particle correlations[4,5] observed in this regime.

To better identify higher order correlations one has to turn to systems with multiple resonances and interactions involving more photons. Six Wave Mixing studies in a single ZnSe quantum well (QW), with laser tuned near exciton and exciton-biexciton resonances, show one must account for at least 6-particle correlations to give a reasonable description of the experimental data[6]. In these experiments evidence of 7^{th} and higher order effects were observed down to the lowest excitaton explored, about a hundred Bohr radii[6]. DCTS modeling of experiments were performed at three levels of sophistication accounting for: a) only the 2-particle and 4-particle correlation in the coherent limit, b) in addition 4-particle correlation that describes incoherent exciton densities, and c) for the 6-point correlation that describe transitions from incoherent exciton densities to two-pair states. Results at both a) and b) level show major discrepancies with experiment, whereas c) is in good agreement, showing that this correlation function is absolutely necessary to describe the data. The origin of these effects is the breakdown of the Random Phase Approximation which assumes at the microscopic level a quasi–stationary limit in which the notion of a mean–field is valid. At low density and on time-scales short compared to the time between collisions one quasi–particle does not interact with enough of its neighbors to feel a mean–field. Instead the effects of nearby quasi-particles can be resolved individually, establishing strong correlations among the carriers. Thus it becomes possible to observe deviations from mean–field theory, in a regime where high order correlations become dominant.

In the case of undoped direct gap semiconductors the correlations are dynamically generated. Although the ground state of the semiconductor has correlations, they do not play a role for *e* and *h* excited near the direct gap. These *e* and *h* behave as particles with mutual interactions without affecting the ground state which, except for providing the dielectric screening, can be considered as rigid. This basic assumption of the DCTS fails when the correlated ground state has low energy excitations that can interact with the photoexcited carriers. This is precisely the case of a two dimensional electron gas (2DEG) in perpendicular magnetic field in the Quantum Hall Effect (QHE) regime. In that case the scattering of the photoexcited *e* and *h* with the collective excitations of the strongly correlated 2DEG becomes non–trivial[7].

Four Wave Mixing experiments on modulation–doped QW's with a 2DEG in the QHE regime and using laser pulses tune for resonantly exciting varying amounts of the lowest

Landau Level (LL1) and the second LL (LL2) have revealed unusual coherent response of this system[8]. In the case of LL1 excitation only, very strong variation of the interband dephasing time vs. filling factor and direct evidence for memory effects were observed. The transition from Markovian to non-Markovian behavior is interpreted as being due to the suppression of the inter-LL scattering relative to the dynamical response of magnetorotons[8]. In experiments exciting varying amounts of LL1 and LL2, spectrally resolved FWM experiments were carried out and compared to measurements performed on undoped QW's with similar parameters[8]. In both cases pronounced beating vs. time delay, Δt, with a frequency corresponding to the LL splitting was observed. However, the striking feature is that there is no FWM emission from LL2 for the doped QW, despite the excitation of a considerable number of carriers into this level, whereas for undoped QW the beats are accompanied by strong emission from both LL1 and LL2 in proportion to the excitation. The tranfer of spectral weight from LL2 to LL1 implies a coherent process by which electrons are promoted to LL2 transfer to LL1 through an inter–LL 2DEG shake–up and strong Coulomb coupling between the two LL's. Whereas that mechanism can explain the spectral weight transfer, the LL1 emission exhibits very odd, almost symmetric, Δt–dependence with a pronounced dip of the order of the pulse duration at $\Delta t = 0$. At present theory only provides a qualitative explanation of the observations.

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Spin in single quantum dot spectroscopy

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The capability to optically probe individual quantum dots (QDs) provides a much sharper picture of the underlying physics of spin in nanostructured semiconductors. In view of the current focus on using spin for information technologies such studies have become especially relevant. For example, the possibility of generating and operating on long-lived spin coherences in semiconductors for quantum information processing requires detailed understanding of the energy structure and interaction dynamics of the electron spin. The requirement for selecting and controlling individual spin states places special emphasis on the study of the spin states in single quantum dots.

Experimental and theoretical results arising from studies of localized electronic spin states in a GaAs QD defined by interface islands will be presented. With high-resolution optical spectroscopy, effects due to the electron spin are clearly resolved in the spectra of single excitons. Fine structure in the spectra arises from the spin of the electron and hole while hyperfine shifts arise from interactions with the spin of the underlying nuclei in the presence of a magnetic field. We find that a theoretical description of our measurements requires a complete consideration in a QD of the exchange Coulomb interaction between electron and hole, the Zeeman interaction and the contact hyperfine interaction between the electronic and nuclear spins.

Optical spectroscopy of single quantum dots at tunable positive, neutral and negative charge states

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We report on the observation of photoluminescence from positive, neutral and negative charge states of single semiconductor quantum dots. For this purpose we designed a structure enabling optical injection of a controlled unequal number of negative electrons and positive holes into an isolated InGaAs quantum dot embedded in a GaAs matrix. Thereby, we optically produced the charge states -3, -2, -1, 0, +1 and +2. The injected carriers form confined collective 'artificial atoms and molecules' states in the quantum dot. We resolve spectrally and temporally the photoluminescence from an optically excited quantum dot and use it to identify collective states, which contain charge of one type, coupled to few charges of the other type. These states can be viewed as the artificial analog of charged atoms such as H^-, H^{-2}, H^{-3}, and charged molecules such as $H_2^+$and H_3^{+2}. Unlike higher dimensionality systems, where negative or positive charging always results in reduction of the emission energy due to electron-hole pair recombination, in our dots, negative charging reduces the emission energy, relative to the charge-neutral case, while positive charging increases it. Theoretical model calculations reveal that the enhanced spatial localization of the hole-wavefunction, relative to that of the electron in these dots, is the reason for this effect.

Luminescence spectroscopy on single quantum dots

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The pioneering work on single dot spectroscopy was published nearly a decade ago [1-8]. Conventional optical spectra, probing many dots at the same time, are broadened inhomogeneous due to variations in size, shape, and composition. Sharp spectral lines in absorption and emission are only observed when individual quantum dots are studied. Spectroscopy with high spatial resolution concomitant with separation of dots in space or in transition energy is used to study the population of single or coupled dots populated with one or a few electron-hole pairs. In the past 4 years nearly hundred papers were published reporting on various aspects of single dot spectroscopy demonstrating the vastly growing interest in this field of research [9]. Photoluminescence (PL) and photoluminescence excitation spectroscopy (PLE) with and without applied magnetic field allows the identification of ground-state and excited electronic levels as well as phonon-assisted processes. The formation of biexcitons (2 electrons and 2 holes in the dot) and filling of higher states is observed in PL with increasing excitation power [10]. In special electrically tunable semiconductor structures it is also possible to study charged excitons and to obtain a well defined controllable population of the dots [11]. In magnetic fields characteristic features with respect to the spin population and spin dynamics are observed, which may be of interest to future quantum information processing. Under resonance excitation a spectrally sharp and tunable photocurrent is obtained in reverse biased single dot photodiodes [12].

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Charged and Neutral Exciton Complexes in Individual InGaAs Quantum Dots

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Recent developments in spatially resolved spectroscopy have now enabled the, almost routine, investigation of *individual* quantum dots. By completely circumventing inhomogeneous broadening effects, such approaches provide direct access to the discrete excitonic spectrum and the modification of the optical properties due to Coulomb interaction and correlation effects. For self-assembled In(Ga)As quantum dots (QDs), the relative magnitudes of Coulomb and kinetic quantisation energies are comparable and the excitonic states are strongly sensitive to the exact number *and* configuration of particles localised in the QD [1]. From this perspective, careful and reliable control of the QD electron-hole occupation is of primary importance when interpreting time integrated optical data.

In this contribution, we present magneto-optical investigations of neutral, negative and positively charged single and multi-excitonic states in single $In_{0.5}Ga_{0.5}As$ self-assembled quantum dots (QDs). Incorporation of the QDs into the intrinsic region of a metal-semiconductor gated structure enables sequential electron or hole charging of the QDs by varying the gate potential (V_g) [2]. Single dots are addressed using micro-photoluminescence (μPL) performed through sub-micro nano-apertures in the gate contact. Both n and p-type samples have been investigated enabling QD charging with up to four electrons ($0 \le N_e \le 4$) or two holes ($0 \le N_h \le 2$) respectively.

The evolution with V_g of the ground state single dot μPL for an n-type sample is presented in fig 1. For large negative V_g, the dot is uncharged and only the charge neutral exciton (X^0) is observed. As V_g reduces, electrons are sequentially loaded into the dot and the emission undergoes a series of pronounced transformations [1]. For charging with a single excess electron ($N_e = 1$), X^0 suddenly disappears and is replaced by the negative exciton (X^{1-}) 5.5±0.7meV to *lower* energy and then by X^{2-} 0.4±0.2meV below X^{1-}. This peak exhibits a weaker satellite, reflecting the possibility for energetically distinct (singlet and triplet) final two-electron states [2]. Most surprisingly, after the next charging threshold ($N_e = 3$) an emission *singlet* (X^{3-}) emerges from the three electron final state. We show that this surprising observation, which indicates a pronounced departure from *Hunds-rule* like state filling, arises since the degeneracy of the *p*-levels is lifted overwhelming the attractive $p - p'$ exchange interactions in the five particle (*4e + 1h*) initial state. For $N_e = 4$ (X^{4-}) an emission multiplet re-appears due the *s-p* electron exchange interaction as for X^{2-} [2]. Finally, the spectrum broadens suddenly at ~-0.2V as the wetting layer is occupied.

Magneto-optical investigations have also been performed to investigate the lateral nature of the many body wavefunctions. These measurements reveal a weak systematic increase of the excitonic *g*-factor from 0.9 to 1.1 as N_e increases from 0→4. In contrast, the diamagnetic shift was found to be very strongly sensitive to N_e, decreasing from 10 to 6±2μeV/T^2 for $X^0 \rightarrow X^{2-}$ before reducing dramatically to *zero* for X^{3-} and recovering to 12±2μeV/T^2 for X^{4-}. This highly surprising observation may

be indicative of the formation of an unusually compact five-particle (*4e + 1h*) state for X^{3-}.

For higher optical excitation levels, neutral and charged bi-exciton recombination is also observed. In contrast to X^{n-}, the energy shift between $2X^0$ and $2X^-$ is very weak ($-0.8 \pm 0.2 meV$), arising from the completely filled s-shell for the $2X^0$ initial state.

As for the electron charging experiments described above, our hole charging measurements reveal a clear evolution of the spectrum from X^0 to X^{1+} and X^{2+} as V_g is varied. However, in strong contrast to the electron charging experiments discussed above hole charging was found to produce much weaker Coulomb shifts, the positively charged excitons being consistently *blue*shifted ($\Delta E(X^{2+}\text{-}X^0) \sim +0.8$meV, $\Delta E(X^{2+}\text{-}X^0) \sim +0.5$meV) when compared with X^0. The origins of these effects, which are reproduced by many body calculations of the charged exciton states, reveal additional information regarding the size of the electron and hole wavefunctions in our QDs.

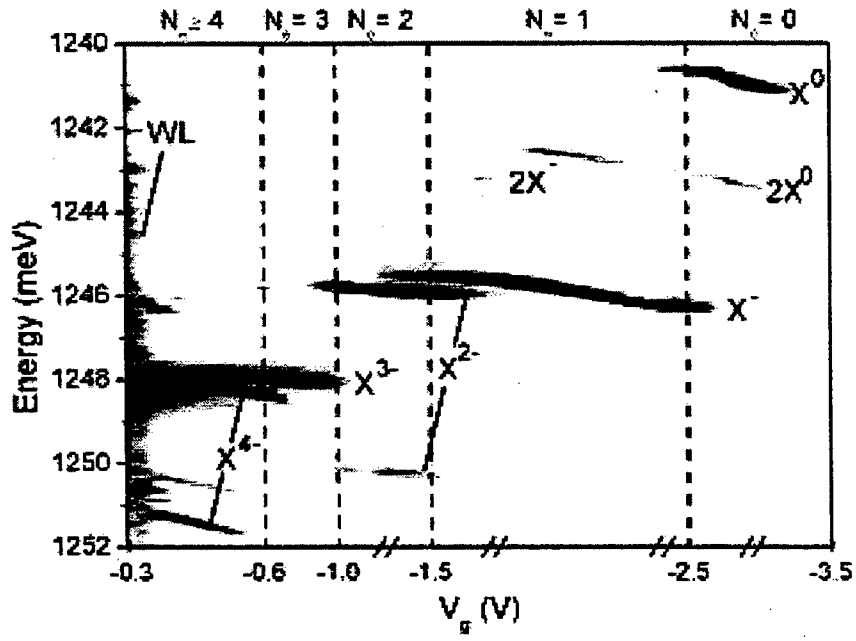

Figure. 1 : Low temperature (T=7K) single dot ground state (s-shell) PL emission as a function of gate potential. Vertical dashed lines denote approximate charging thresholds.

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Photonic Band Gap Materials: A Semiconductor for Light

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Photonic band gap (PBG) materials are a new class of dielectrics which represent a major new frontier in quantum, nonlinear, and classical optics. Unlike semiconductors which facilitate the coherent propagation of electrons, PBG materials execute their novel functions through the coherent localization of photons. I describe the micro-fabrication of three-dimensional PBG materials. When a PBG material is doped with impurity atoms (or other two-level systems) which have an electronic transition that lies within the gap, spontaneous emission of light from the atom is inhibited. Instead, the photon forms a bound state to the atom. This has dramatic consequences for collective light emission from a large number of atoms and for the interaction of such atoms with an external laser field. I describe the design of an optical micro-transistor based on collective switching of two-level atoms near a photonic band edge, by external laser field.

Waveguide-based 2D photonic crystals : a few building blocks towards 3D confined structures

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Photonic crystals (PCs) in the visible range are slowly emerging from a conceptual phase to physical implementations. In the past few years, several 3D fabrication techniques have been demonstrated which lead/should lead to the observation of full 3D bandgaps. However, 3D PCs do not easily yield *sizeable physical effects* such as the control of spontaneous emission or lifetime changes, or in structures that could be exploited in the optoelectronics field.

On the other hand 2D PCs in thin-slab or waveguide structures open a number of new possibilities in optoelectronics or in the realization of various integrated optics components such as mirrors, micro-resonators, couplers, etc. In that case waveguiding in the third direction orthogonal to the PC design leads to full 3D confinement of optical modes.

Earlier physics studies consisted in establishing the basic kinematic properties of 2D PCs such as *transmission, reflexion and diffraction coefficients*. It is now well established that for a variety of structures and materials excellent, quasi-intrinsic properties can be obtained[1]).

To further assess the potential of PCs in optoelectronics applications, it is essential to evaluate in-depth specific properties of these structures beyond their basic kinematic properties. For instance, *radiation losses* in the substrate or superstrate around the slab represent an unwanted loss mechanism for resonator or integrated optics purposes, or a welcome extraction mechanism for light in LEDs. We have developped an analytical perturbation method which gives a realistic estimate of such radiation losses as a function of the basic system parameters (hole diameter and height, index contrasts of super- and sub-strate with respect to the core). Its results are described by an imaginary index of refraction in the air holes representing radiative losses and give trends in excellent agreement when compared with existing 3D calculations or to quantitative experimental results. They thus provide a universal tool to make predictions and improve 2D PCs[2].

Several building blocks for photonic integrated circuits have been studied. Very high-performance devices can be foreseen from the measured quality factors in excess of 1000 Recently, we have demonstrated the association of two coupled devices made from photonic crystals, a photonic crystal bounded waveguide and hexagonal PC microcavities. A specific coupling mechanism between cavity and waveguide is observed, based on optical tunneling between cavity and waveguide modes and subsequent mode conversion in the waveguide[3].

Losses can be engineered towards useful applications concepts. We have recently used new PC structures to yield LEDs with ultimate emission efficiencies, although with a fully planar process.

It thus appears that photonic crystals might have a huge impact in various essential areas of future technologies, although not exactly in the way originally predicted.

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Photonic Bandgap Crystals and Devices

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Much interest has been drawing in photonic crystals in which the refractive index changes periodically. A photonic bandgap is formed in the crystals, and the propagation of electromagnetic waves is prohibited for all wave vectors. Various important scientific and engineering applications such as control of spontaneous emission, zero-threshold lasing, very sharp bending of light, trapping of photons, and so on, are expected by utilizing the photonic bandgap and the artificially introduced defect states and/or light-emitters. Recently, we have succeeded in developing complete 3D photonic crystals with sufficient bandgap effects at near-infrared wavelengths (1~2μm) based on a method where III-V semiconductor stripes are stacked with the wafer-fusion and the laser-beam assisted very precise alignment [1]. In this presentation, I at first review our approach to create the full 3D photonic bandgap crystals at near-infrared wavelengths and possible applications to ultrasmall optical integrated circuits.

2D photonic crystals are also promising since specific (not almighty, but important) functional devices can be realized even though the control of light is limited two-dimensionally. Thus far, we have investigated novel functional devices utilizing 2D photonic crystals. One example is a 2D photonic crystal laser with multi-directionally distributed feedback effect in 2D photonic lattice structure [2]. It is expected that the device can work as a high-output power surface-emitting laser, which can oscillate in very large area with single mode and desired polarization. The other is a device utilizing a single defect in 2D photonic bandgap structure [3]. The defect traps the photons which propagate through a waveguide formed in 2D photonic crystal slab and emits them to free-space. This phenomenon is very promising for the actual application to an ultra-small optical device with a function of dropping (or adding) photons with various energies from (or into) optical communication traffic (fiber). There are many other important applications by utilizing the strong localization of photons at the defect such as enhancement of nonlinear optical phenomena, and trapping of nano-particles. In this presentation, I also describe the results on the above unique 2D devices and/or phenomena.

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Contributed Papers

Poster Session
4 – 7 PM

TRION SPECTRA IN SEMICONDUCTOR NANOSTRUCTURES

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In the optical spectra of semiconductor nanostructures with moderate doping, charged excitons (trions) show up as a distinct line below the exciton transition. We develop a consistent density-matrix approach [1] for the linear optical susceptibility which is exact to lowest order in the excess density (doping). Concerning spin, the trion separates into a singlet channel (majority spins antiparallel) and a triplet one (spins parallel). Further, we distinguish between electron trion (eeh) and hole trion (ehh).

The trion binding energy depends on the electron-hole mass ratio $\sigma = m_e / m_h$ and the confinement strength. Fig. 1 shows calculated results for a prototype quantum wire with fixed confinement, varying the mass ratio σ independently. For realistic mass ratios, only the hole trion exhibits a triplet bound state. We have converted the trion equation from density matrix theory into a time-dependent three-particle Schrödinger equation in relative coordinates, with a parametric dependence on the trion center-of-mass momentum Q. In the spectrum, we found for the trion bound state an asymmetry towards lower photon energies due to carrier recoil ($Q \neq 0$). Analogous quantum well calculations agree well with experimental photoluminescence data at different temperatures [2]. The (sharp) exciton line comes out reduced in oscillator strength. Further, a wing extends above the exciton which is related to exciton-electron scattering (beyond perturbation theory). A low-energy tail of the exciton is again due to carrier recoil (Fig. 2). These subtle findings still await an experimental verification.

The presented density-matrix theory and its numerical implementation allows to explain successfully further features including radiative trion lifetimes [2] and the influence of a static electric field (quantum-confined Stark effect) [1].

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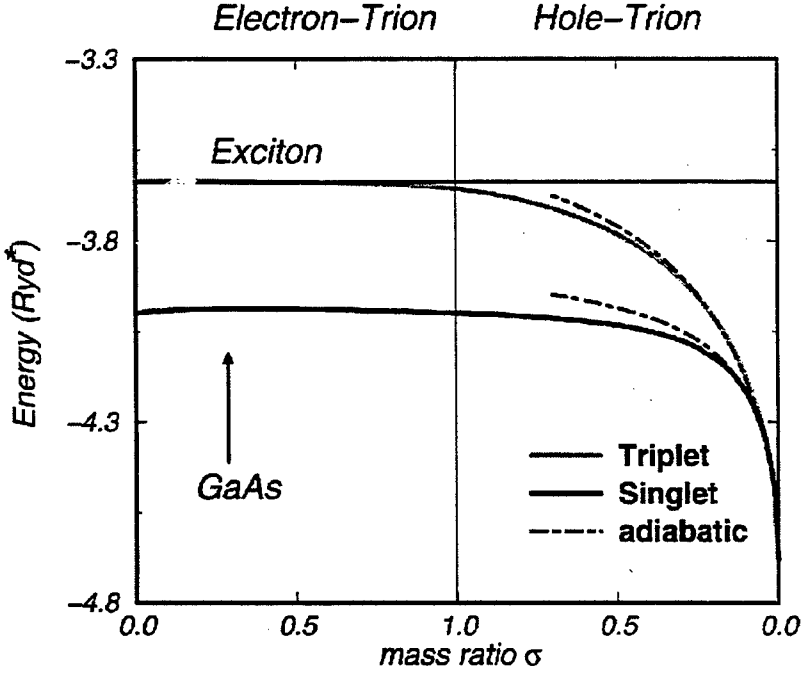

Fig. 1: Calculated trion binding energy (relative to the confinement level) for a prototype quantum wire with circular cross section, as a function of mass ratio $\sigma = m_e / m_h$. The confinement has been adjusted to give a wire exciton binding energy of 3.7 Ryd* (Ryd* is the bulk exciton binding energy). Full curves – numerical solution of the trion equation, chained – adiabatic result valid close to the classical limit (H_2^+ like state).

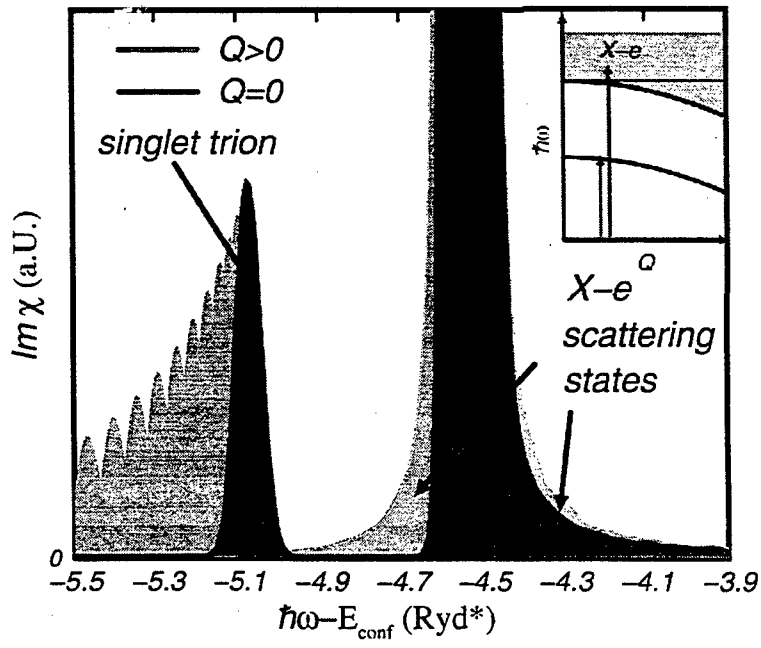

Fig. 2: Linear optical absorption of a quantum wire with excess electrons in the singlet channel. The mass ratio is $\sigma = 0.3$ (GaAs). Calculated spectra for different center-of-mass momenta Q

of the initial electron (see inset) are superimposed with equal weight. A phenomenological Gauss broadening of 0.07 Ryd* is assumed.

Semiclassical Treatment of the Electron-Hole Long-Range Exchange Interaction in Semiconductor Nanocrystals

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The electron-hole exchange interaction in excitons confined in semiconductor nanocrystals (NCs) of the radius less than the bulk exciton Bohr radius has attracted much attention in recent years. Such an interest stems from the fact that, due to the strong size quantization of the electron and the hole, the exchange-induced exciton-level splittings become very large compared with those in bulk semiconductors. These splittings were observed in CdSe NCs embedded in glassy matrices and polymer films and were intensively studied by a number of experimental groups [1-3].

The electron-hole exchange interaction is usually divided into the long-range (non-analytical) and short-range (analytical) parts and can be accounted for in different ways. According to Ref. [4], the term "mechanical exciton" stands for the case where only direct Coulomb interaction between the electron and the hole is taken into account. The "Coulomb exciton" is obtained by the further inclusion of the short-range exchange plus either the long-range electron-hole exchange interaction (scheme [A]) or the mechanical exciton interaction with the exciton-induced macroscopic longitudinal electric field (scheme [B]).

The theoretical study of the electron-hole exchange interaction for both bulk materials and NCs was mainly performed following the scheme [A]. In the framework of the effective-mass approximation the theory of the electron-hole exchange interaction in semiconductor NCs of spherical shape was constructed in Refs. [5, 6].

In the present study we show that the exchange-induced splittings of the ground-state exciton level in semiconductor NCs can be equivalently obtained following the

scheme [B]. We derive the expression for the polarized-light-induced linear macroscopic polarization of the semiconductor NC in terms of the effective-mass approximation. Once the polarization is written, only Maxwell equations are used to obtain the frequency renormalization of the exciton resonance. Note that to solve the same problem following the scheme [A], one has to deal with 8×8 Hamiltonian [5, 6]. The difficulty of this problem is reflected in the scheme [B] by the fact that the linear nonlocal susceptibility has a tensor character. We show that the nonlocal tensor susceptibility can be replaced by an effective local scalar one and discuss a simple physical picture associated with this model.

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Time-Resolved Differential Transmission Measurement of Phonon Bottleneck in Self-Organized Quantum Dot Electronic Relaxation

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A "phonon bottleneck," or a suppression of carrier relaxation rates, is predicted for semiconductor self-assembled quantum dots because single-phonon-mediated scattering processes will be inhibited due to energy and momentum conservation requirements[1-3]. However, many groups, including our own[4], observed fast interlevel relaxation and attributed it to Auger-type processes[5-7], intradot electron-hole scattering[3,8], or multiphonon processes[5,9]. We observe the bottleneck when we remove these fast relaxation processes by performing a differential transmission (DT) carrier capture experiment at low carrier densities.

The sample is an undoped heterostructure with four layers of $In_{0.4}Ga_{0.6}As$ quantum dots grown by molecular beam epitaxy. Photoluminescence data on this sample confirm that the excited state interband transition (E2H2) is centered near 920 nm (1.35 eV) while the ground state transition (E1H1) is centered near 980 nm (1.27 eV)[4].

The DT measurements are carried out at 40 K with a pump-probe setup. For tunable pump and probe pulses, white light sources are generated using a 100-fs 250-kHz regenerative amplifier output. We detect the DT signal with a lock-in amplifier referenced to a 2-kHz chopper.

Results from our carrier capture experiments are shown on Fig. 1. Here, electron-hole pairs, with a density of less than one pair per dot, are photoinjected into the continuum above the dots. The n=2 time scans reveal that after a very fast capture into and fast relaxation out of the dot excited state, a long-lived population persists and decays at a rate slower than the recombination rate. We believe that this slowly decaying signal is a clear sign of the predicted phonon bottleneck.

We understand this phonon bottleneck signal by considering geminate and non-geminate capture processes for electrons and holes (Fig. 2). For the geminate capture case, intradot electron-hole scattering and other Auger-type processes would dominate in producing a fast relaxation. In the non-geminate case, however, such scattering events would be suppressed because of the spatial separation of the electrons and holes. We fit the DT time scans with two simple sets of rate equations based on this model. The solutions reveal that the geminate capture and intersubband relaxation times are consistent with those in our previous measurement[4] while the non-geminate component contributes a bottleneck signal which decays with a long time constant of 750 ps. We believe that this bottleneck signal is not originating from the heterostructure surrounding the dots, the possible strain-induced defects, mixed signals from the ground states, excitation-induced thermal effects, or from the presence of unintentional doping of the dots.

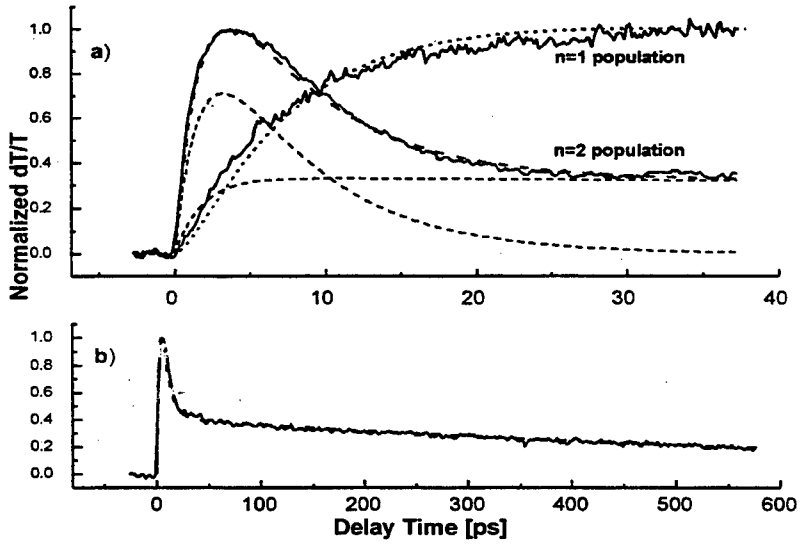

Figure 1. DT time scans taken at 40K. a) Non-resonantly pumped DT time scans for n=1 (980 nm) and n=2 (910nm) dot levels with rate equation fits (dark dashed lines). The geminate and non-geminate components of the n=2 fit are given as light dashed lines. b) DT time scan of the n=2 level with long delay.

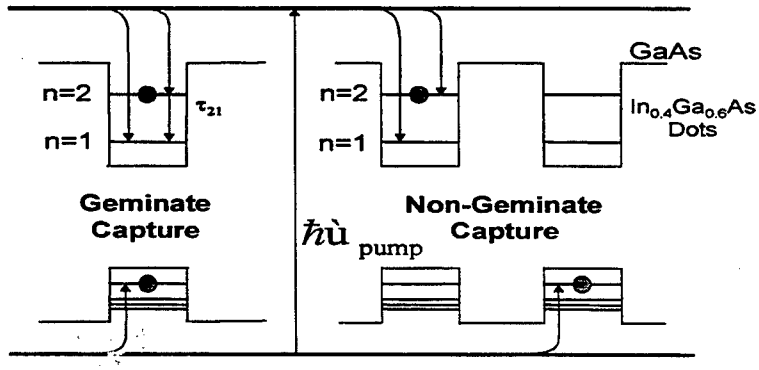

Figure 2. Carrier capture model with geminate (electron and hole are paired) and non-geminate capture configurations.

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RELAXATION OF ELECTRON ENERGY IN POLAR SEMICONDUCTOR DOUBLE QUANTUM DOTS

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Various proposals of how to realize the quantum computation have been considered including the scalable solid state nanostructures (see e.g. [1]). In these structures the qubit states can be represented e.g. by the orbital motion of a single electron in a 0D nanostructure. It is well known that the electron energy relaxation rate in a single quantum dot of a polar semiconductor is considerably large (see e. g. [2]). The theoretical interpretation of this effect was given recently [3-6] in terms of the multiple scattering of the electron on the polar modes of the optical phonons. Although the fast relaxation can be favourable for the quantum dot lasers, from the point of view of the quantum computation it is desirable to have the possibility to lower the relaxation rate effectively to such an extent that the unitary operations of the quantum gates could be performed in a safe manner.

We study theoretically the electron-energy relaxation process based on the multiple electron-LO-phonon scattering. The electronic relaxation rate is computed numerically for a realistic model consisting of a single electron in an asymmetric pair of tunneling coupled quantum dots, each having a single electronic state orbital. The electron is assumed to couple to the LO optical phonons (bulk modes). The dependence of the electron-energy relaxation rate on the magnitude of the inter-dot electronic tunneling parameter, on the electronic energy-level separation and on the lattice temperature, is computed in this GaAs-based double quantum dot structure. Similar dependencies of the optical data like the line-shape and the line-width of the electronic spectral densities corresponding to the two electronic orbital states are calculated.[&]

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COHERENT SPECTRAL OSCILLATIONS IN MULTI-WAVE MIXING

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Ultrafast degenerate four-wave mixing (FWM) has been applied successfully to study the dynamics of optical excitations in bulk semiconductors and nanostructures and, in particular, revealed the importance of Coulombic correlations and quantum kinetic processes. Theoretically such phenomena are analyzed using semiconductor Bloch equations (SBE) including the important dynamics of many-body Coulomb correlations beyond the Hartree-Fock approximation. While the coherent optical response is well understood in the low-intensity limit (third order in the electric field) much less is known beyond this regime although at even moderate excitation intensities fifth order processes begin to play a significant role in semiconductors.

Here we report on measurements of the FWM spectrum emitted in the direction $2\mathbf{k}_2-\mathbf{k}_1$ in the presence of a delayed third pulse with direction $\mathbf{k}_3$ nearly perpendicular to the surface of a ZnSe/ZnMgSe single quantum well. Due to phase matching the third pulse has to be taken into account at least up to second order and thus changes of the ordinary two-pulse FWM signal induced by the third pulse are at least of fifth order in the fields. The measured signal can be thought of as a combination of FWM and six-wave mixing (SWM). Since the third pulse contributes at least to second order and since it comes from a direction that is different from the directions of the first two pulses and the signal, this measurement includes simultaneously contributions from wave-mixing and pump-probe type experiments. We find strong coherent interactions among the excitations induced by all three pulses. In particular, we find coherent oscillations in the spectrum with a period inversely proportional to the delay of the third pulse (see Fig. 1). These spectral oscillations are studied using delay time, polarization and intensity dependent measurements. The experimental results are in good agreement with microscopic SBE calculations which include four-particle Coulomb correlations up to fifth order.

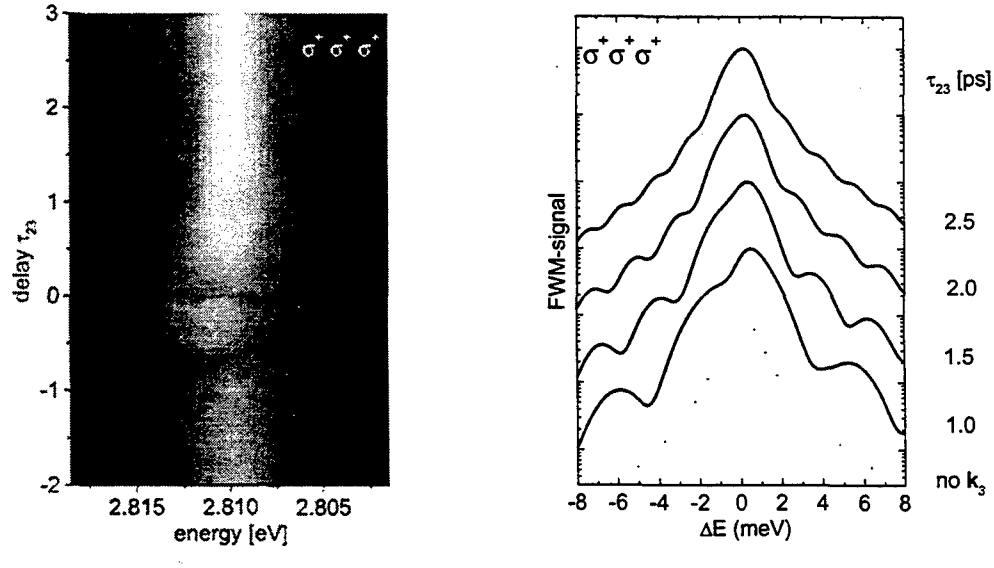

Fig. 1: Contour plot of the multi-wave signal for co-circular polarized fields (left) and SBE calculated spectra at various positive delay times of the third pulse (right). The zero of the energy scale coincides with the position of the exciton resonance.

Thermal redistribution and dephasing of localized excitons in CdSe/ZnSSe quantum dot structures

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Semiconductor quantum islands have received much attention recently because of their superiority for possible applications in opto-electronic and all-optical devices, where improvements like the reduction of laser threshold or the decrease of scattering processes and high optical non-linearities due to the modified density of states are predicted. Driven by the current search for blue-green laser structures in the visible spectral range, the fabrication and optical characterization of self organised II-VI quantum islands has recently attracted intensive research activities. Only little is known about the coherent properties of these structures, giving information about the formation of biexcitons and scattering processes of localised island states.

In this contribution we study the thermal redistribution of excitons in self-organised multiple stacked CdSe/ZnSSe island structures grown by metalorganic vapour phase epitaxy using temperature dependent photoluminescence (PL) and spectrally resolved four-wave mixing (FWM). Temperature dependent PL measurements show a blue-shift of the emission maximum above 50 K which is attributed to a thermal activation and redistribution of excitons of more localised to less localised excitons and to delocalised ZnCdSSe layer states. Spectrally resolved FWM at low temperatures reveals a multi-exponential decay of the photon echo indicating the presence of differently localised exciton states at comparable transition energies. A redistribution of localised excitons is indicated by temperature dependent FWM measurements which show a two-exponential dephasing at temperatures below 55 K and a mono exponential decay above, in agreement to the thermal behaviour of the PL band (see Fig. 1). In addition polarization dependent FWM measurements identify the formation of biexcitons with a biexciton binding energy of 12 meV which is smaller by a factor of 2 compared with CdSe/ZnSe island structures. This finding may be due to a weaker localisation of excitons in the CdSe/ZnSSe samples which corresponds to the observation of a thermal activation of excitons above 50 K.

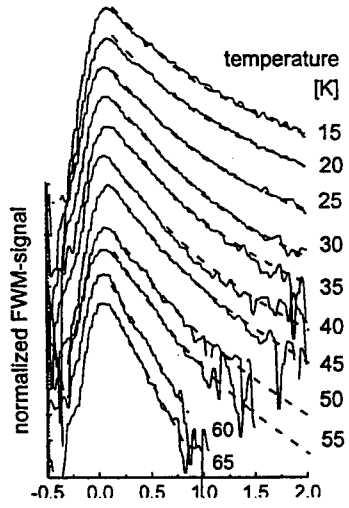

Fig. 1: FWM-traces at signal maximum as a function of temperature. The energetic distance between the PL-maximum and the excitation position was kept constant over the whole temperature range. The dashed lines show fits using a two-exponential function up to 55 K and a mono-exponential function above 55 K.

Diffusion-controlled subpicosecond carrier dynamics in ErAs:GaAs superlattices

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Recent findings [1-4] suggest that a material consisting of equidistant layers of self-assembled ErAs islands embedded in a GaAs matrix (ErAs:GaAs) [4] is a promising altemative to LTG-GaAs in ultrafast optoelectronic switching applications. Compared to LTG-GaAs, this new material exhibits some intriguing advantages. First of all, the microstructure, which controls the electronic properties, can be engineered in a straightforward way by means of molecular beam epitaxy (MBE). As far as optoelectronic devices are concerned, the ErAs island superlattice (SL) represents a remarkable breakthrough, since it is conceivable to integrate such a SL into smaller bandgap materials like InAs. This may point the way for realizing materials for ultrafast photoconductive switches at typical communication wavelengths.

To investigate the carrier dynamics in ErAs:GaAs as a function of the ErAs SL period L, we have grown seven different ErAs:GaAs samples on semi-insulating (100) GaAs substrates by MBE with L varying between 40 nm and 400 nm. On top of these samples, we structured photoconductive switches consisting of a 3µm-broad gap in the center conductor of a metallic coplanar waveguide (CPW). A schematic topview and cross section of the samples are given in the insets of Figs. 1 and 2, respectively.

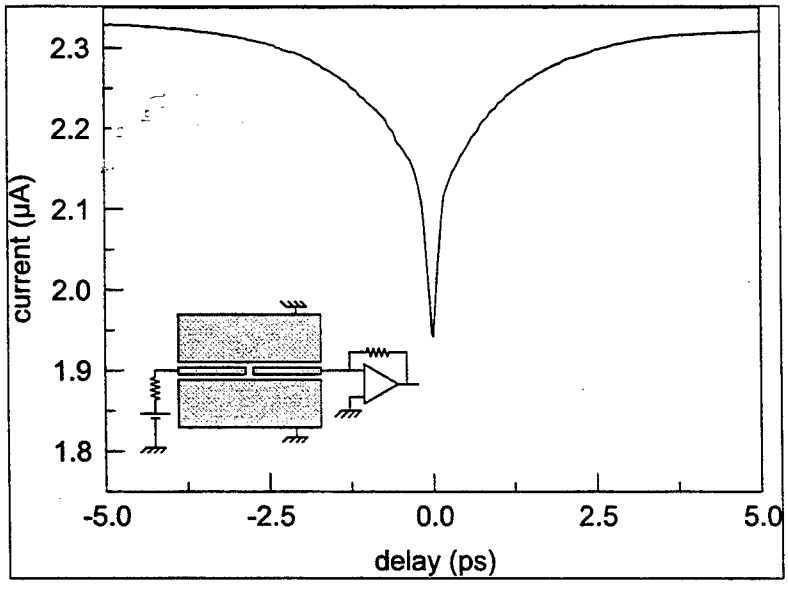

Fig. 1. Autocorrelation trace for a sample with L =100 nm at U = 2.25 V and P = 0.5 mW per beam yielding τ = 2.3 ps. The inset sketches the CPW and the measurement circuitry.

We determine the electron lifetime τ in each sample under applied electric fields by performing current autocorrelation measurements on these photoconductive switches. Thereto, we illuminate the gap of the CPW in a typical collinear pump-probe geometry with 140fs-long Ti:Sa laser pulses centered at a wavelength of 800 nm and measure the resulting photocurrent as a function of the delay between the two pulsetrains. Fig. 1 shows an autocorrelation trace for a sample with L = 100 nm taken at a bias voltage of U = 2.25 V and an average power of P = 0.5 mW per pulse train. By evaluating the timescale of the strong decrease of the photocurrent around the temporal overlap of the two laser pulses, we directly find τ [5].

As shown in Fig. 2, τ is easily tunable between 450 fs and 17 ps by varying L from 40 nm to 400 nm. The quadratic dependence of τ on L can be understood in terms of a simple diffusion model, where the lifetime of each electron is limited by the time it needs to travel from its point of creation to the trapping centers in the SL planes. Applying this model to our data yields an ambipolar diffusion constant of 9.0 cm^2/s that is in good agreement with a value estimated using electron and hole mobilities.

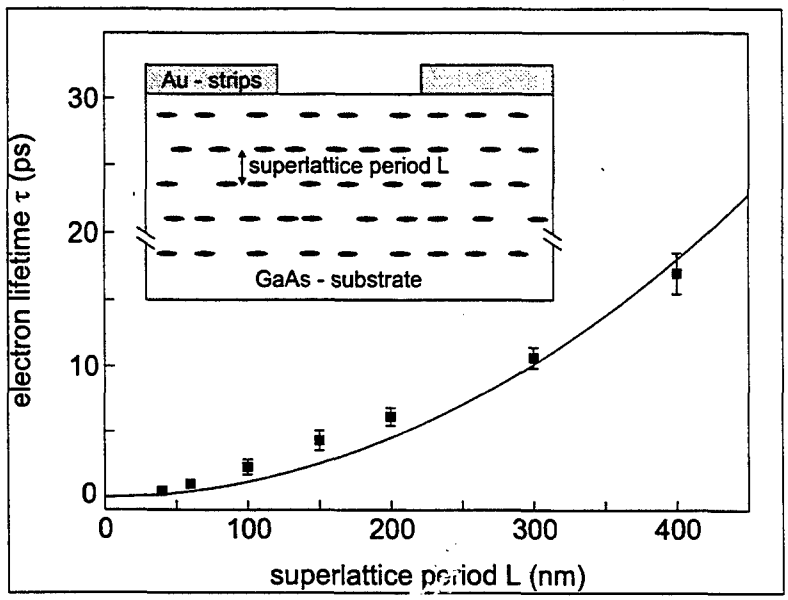

Fig. 2. Measured electron lifetime τ (dots) as a function of the superlattice period L at U = 2.25 V and P = 0.5 mW per beam and model calculation of the electron lifetime assuming diffusional motion (solid line). The inset shows a cross section of the ErAs:GaAs superlattice and the CPW.

This easy tunability of the subpicosecond carrier dynamics by means of MBE is a unique feature of this novel material class and may point the way for realizing device applications such as THz sources or high-speed optoelectronic circuits based on ErAs:GaAs, since a broad band of the THz spectrum can be covered in a controllable way with this material.

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Coherent Dynamics and Radiative Lifetime of Bipolaritons in CdS

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In this contribution we study the dynamics of an optically driven/decaying coherent ensemble of excitons, photons, and excitonic molecules in bulk CdS and examine the validity of the bipolariton representation. In FWM-experiments in backward-scattering geometry we exploit the different group velocities of lower and upper branch polaritons and excitonic molecules to distinguish between propagation and dephasing effects. We report the first measurement of the radiative lifetime τ^{XX}_{rad} of bipolaritons in high-quality CdS and show that the bipolariton distribution in **k**-space is mirrored both in the spectral response of the bipolariton-polariton transition and in the dephasing time of bipolaritons. The measured exponential rise time yields a bipolariton dephasing time of $T_2(T=5K)$ = 4.0 ps and the corresponding decay width $\Gamma_{dec}(T=5K)$ = 0.33 meV. For the zero-temperature extrapolated $\Gamma_{dec}(0K)$ we obtain $T_2(0K)$ = 4.8 ps. In the spectral response of the molecule-mediated FWM-signal, a double-peaked structure with an energy splitting of 0.7 meV is observed. We attribute this double-peaked structure to a hot, unrelaxed distribution of molecules in agreement with calculations of the bipolariton distribution in **k**-space. To compare the experimentally obtained dephasing times with the theoretical bipolariton radiative lifetime, we adapt an exactly-solvable bipolariton model in order to calculate nonperturbatively the radiative correction to the binding energy of molecules in hexagonal crystals. We discuss both the real part of the radiative correction (the Lamb shift) of the molecule energy and the imaginary part which yields τ^{XX}_{rad}. The calculation yields τ^{XX}_{rad} ~ 2.8 ps, indicating indeed the approaching of the $T_2 = 2T_1$ limit in our experiment.

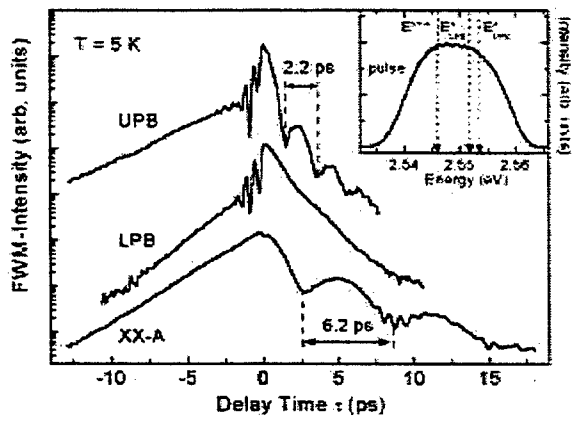

Fig. 1
Intensity of the TI backward-scattered FWM-signal as a function of delay time τ. The FWM-signal is measured at the energies of the UPB, LPB, and XX-A transition in bulk CdS at T=5 K. The curves are displaced for clarity. The inset shows the spectrum of the exciting laser pulses centered at 2.549 eV with an intensity of I_{pulse} ~ 64 nJcm^{-2} and a bandwith of 18 meV (FWHM). Bipolariton signatures arise from (i) a slow exponential rise of the XX-mediated FWM-signal at negative delay times, and (ii) at positive delay times, a modulation of the XX-A signal with an oscillation period of 6.2 ps. The modulation of the UPB-signal by a 2.2 ps- oscillation for $\tau > 0$ is given by the LT-energy splitting of 1.9 meV.

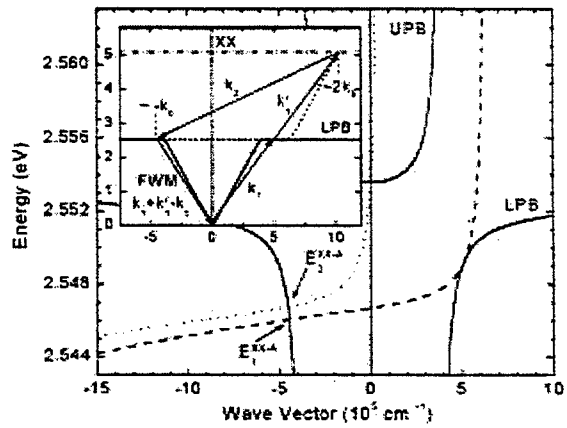

Fig. 2
Graphic solution of the energy-momentum conservation law to determine the energy of the backscattered FWM-response at the XX-A transition. The spectral point marked by $E_1^{XX-A}(E_2^{XX-A})$ originates from the induced transition from XXs with wave-vector ~$2\mathbf{k}_0$ (~$\mathbf{k}_0$) by LPBs. The oscillation for $\tau > 0$ at the XX-A transition (Fig. 1) can be explained by the interference of the two inducing polaritons with an energy difference $E_{LPB}^{A}(k_2 \sim 3k_0) - E_{LPB}^{A}(k_2 \sim 2k_0)$ ~ 0.6meV which nicely agrees with the measured oscillation period of 6.2ps. Inset: Scheme of the optical transitions generating the backward scattered FWM signal at the energy of the bipolariton-polariton transition. Bipolaritons are excited by the LPB + LPB -> XX process.

SCATTERING OF POLARITONS BY A TWO DIMENSIONAL ELECTRON GAS IN A SEMICONDUCTOR MICROCAVITY

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Recently, there is an increase interest in the distinct scattering and dephasing mechanisms of microcavity (MC) exciton polaritons (MCP) as compared to those of bare quantum well (QW) excitons. Most studies have been devoted to elastic and inelastic polariton-polariton (exciton)[1] or polariton-phonon scattering processes[2]. In this work we report on a study of MCP's - free electron scattering processes via their reflection linewidth in an *AlAs/AlGaAs* microcavity containing *GaAs* quantum wells in which a variable density electron gas is photogenerated[3]. The main experimental findings (at T=80K) are: (a) the electron-polariton scattering mechanism is very efficient, as compared to both polariton-polariton or phonon-polariton scattering, and have a strong effect on the MCP's linewidth. (b) A transformation is observed from a strong to weak exciton-cavity mode coupling at a very low photoexcitation intensity (As shown in Fig. 1a), as compared to the photoexcitation intensities required for MCP bleaching[4]. (c) The dependence of MCP's linewidths on the MC detuning energy in the presence of electron gas (Fig. 1b,c) shows very distinct features which cannot be explained by a simple linewidth averaging model (Fig 2a): The linewidth of the lowest polariton branch shows a clear suppression while that of the other branches show enhancements at narrow detuning energy ranges.

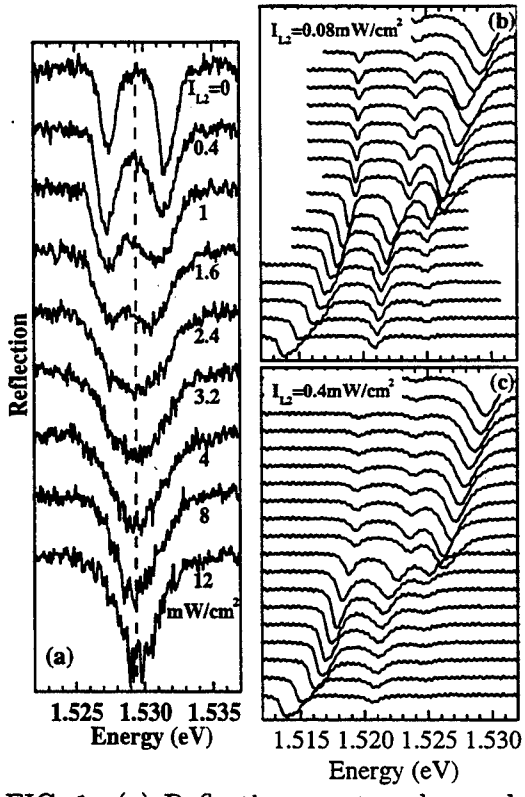

FIG. 1. (a) Reflection spectra observed at exact resonance ($\delta = 0$) for different photoexcitation intensities I_{L2}. The dashed line marks the bare MC mode energy. Reflection spectra measured for different detuning energies δ, taken with (b) $I_{L2} = 0.08mW/cm^2$ and (c) $I_{L2} = 0.4mW/cm^2$.

In order to explain the above results, a theoretical model is developed for the dynamics of MCP's in a presence of a two-dimensional electron gas (2DEG). The model is then used to predict the cavity polariton linewidths in the strong exciton-photon coupling regime. The model is based on calculating the exciton-electron direct and exchange interaction matrix elements, from which we derive the scattering rates of bare excitons, as a function of

their initial momentum (or energy).

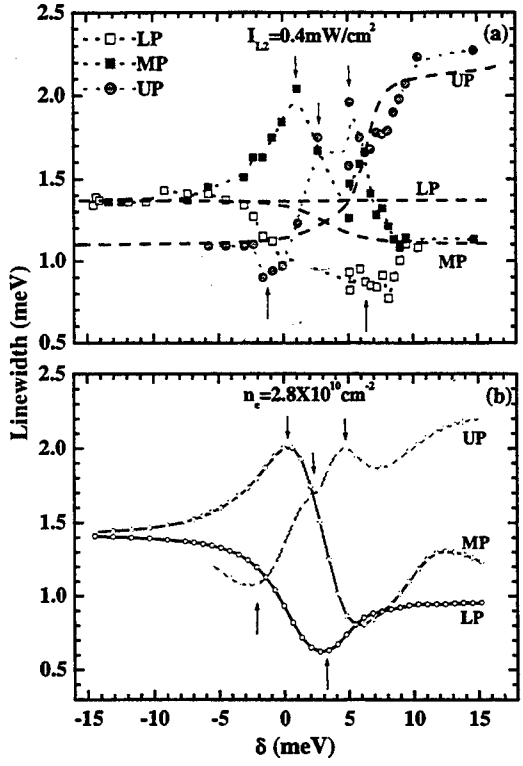

FIG. 2. (a) Experimental (symbols) MCP linewidths, measured with $I_{L2} = 0.4mW/cm^2$. The dotted lines are guides to the eye. The dashed lines are the prediction of a simple linewidth averaging model. This model cannot reproduce the experimental results (b) Model calculated MCP linewidths for $n_e = 2.8 \times 10_{10} cm^{-2}$ (As described in the text). The down pointing arrows mark the linewidth peaks while the up pointing arrows mark the linewidth minima

This exciton-electron interaction is found to be an efficient scattering mechanism with a characteristic exciton linewidth of $1meV$ at $n_e = 10^{10} cm^{-2}$, compared with an exciton linewidth of $\approx 0.2meV$ for exciton-phonon interaction at T=80K. We then extract the bare exciton line shape by convolving its initial distribution function with the Lorentzian distribution that is due to the scattering processes. This result in an n_e dependent, asymmetric bare exciton lineshape. Inserting these calculated hh and lh excitonic line shapes into a semiclassical linear dispersion model of the microcavity structure, we obtain the cavity polariton linewidths as is seen in Fig. 2b. All the above observations are well explained by this asymmetric line shape of the bare exciton, resulting from its scattering with the free electrons. The dominant electron-polariton scattering mechanism can also be considered as a good candidate for achieving an efficient polariton final-state stimulation. This is different from the previous suggested mechanisms, mostly since one of its constituents (the electron) is a fermion.

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Parametric scattering of cavity polaritons : phenomenological vs microscopic models

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Four particle correlation effects have been revealed in a number of FWM experiments, which resulted in great advance in the understanding of the Coulombic memory effects. Within $\chi^{(3)}$–limit the optical response is govern by the exciton polarization and population as well as two-exciton coherence, in which four particle correlation effects play the major role. The temporal evolution of the two-exciton coherence can be described by building the hierarchy of carrier correlations in terms of order of the light wave amplitude.[1] However, a comprehensive description here requires a rather advanced modeling even under assumption on the coherent carriers dynamics. Alternatively the third-order nonlinearity at the fundamental band edge can be described in terms of the renormalized interaction of *1s*-excitons allowing one to estimate the correlation correction to the exciton meanfield energy. Being essentially phenomenological this description results in the same evolution equation for the *1s*-excitonic polarization as consistent microscopic theories [2].

We have found [3] that the FWM of cavity polaritons brings the ideal situation to examine the four-particle correlation effects, which can be treated in terms of the polarization dependent exciton anharmonicity that gives rise to the parametric scattering of cavity polaritons. In this report, in order to clarify the physics underlying such Bosonic model, we re-examine the results of the frequency- and time-domain FWM measurements in GaAs/AlGaAs microcavity by comparing predictions of the polariton scattering model and T-matrix calculations [4]. This allows us to visualize the relationship between the phenomenological and microscopic approaches and to find out in what extent the higher order correlations can be taken into account in the frame work of two-body exciton-exciton interaction model. In particular, we are focused on the relative contribution from the bound and unbound two-exciton states to the FWM signal and also on the role of the excitation induced dephasing.

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Coherent Optical Nonlinearities in Normal Mode Microcavities

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The nonlinear optical response of quantum-well (QW) microcavity systems has often been discussed in terms of "polaritonic nonlinearities". At the same time, tremendous progress has been made in recent years in understanding the microscopic origin of the polarization-dependent nonlinear optical response in bare quantum wells, including a consistent theory of Coulomb correlation-induced nonlinearities in the coherent regime. We investigate the nonlinearities of normal-mode microcavities (NMC's) at the same level and demonstrate that the microscopic theory accounting for the bare-QW response also qualitatively accounts for the normal-mode nonlinear response.

We report here an extensive series of pump-probe experiments and calculations, investigating the time-resolved reflectivity of an NMC as a function of pump and probe polarization, pump fluence and detuning. The probe reflectance spectra for co-circular polarization are shown in figure 1. Both modes exhibit a strong blue shift and saturation. There is additionally a strong gain feature on the low-energy side of the lower normal mode. Here, the probe polarization is induced at the same spin states as the pump polarization, and, in this case, excitation induced dephasing is the dominant process in the nonlinear response of the probe. The second-order Born approximation, which includes terms up to quadratic order in the screened Coulomb interaction, is able to reproduce the main features of the experimental results. Figure 2 shows the spectra of the nonlinear optical response for cross-circular polarization. No gain feature is seen on the lower mode, which, however, displays a red shift. This is not surprising, since under cross-circular polarization conditions the exciton can exhibit a red shift in bare QW's as well. Additionally, the upper normal mode exhibits the appearance of a new resonance on the low energy side; this arises from biexcitonic correlations. For cross-circular polarization, biexcitonic correlations are prominent, and dephasing contributions to the probe polarization are substantially reduced, because the probe pulse interacts with those spin states not populated by the pump pulse. To investigate this case we have used an expansion of the microscopic equations in terms of correlation functions and include contributions up to 5th order in the applied optical fields as well as biexcitonic correlations. The biexcitonic resonance at the red side of the upper mode is well reproduced by this calculation.

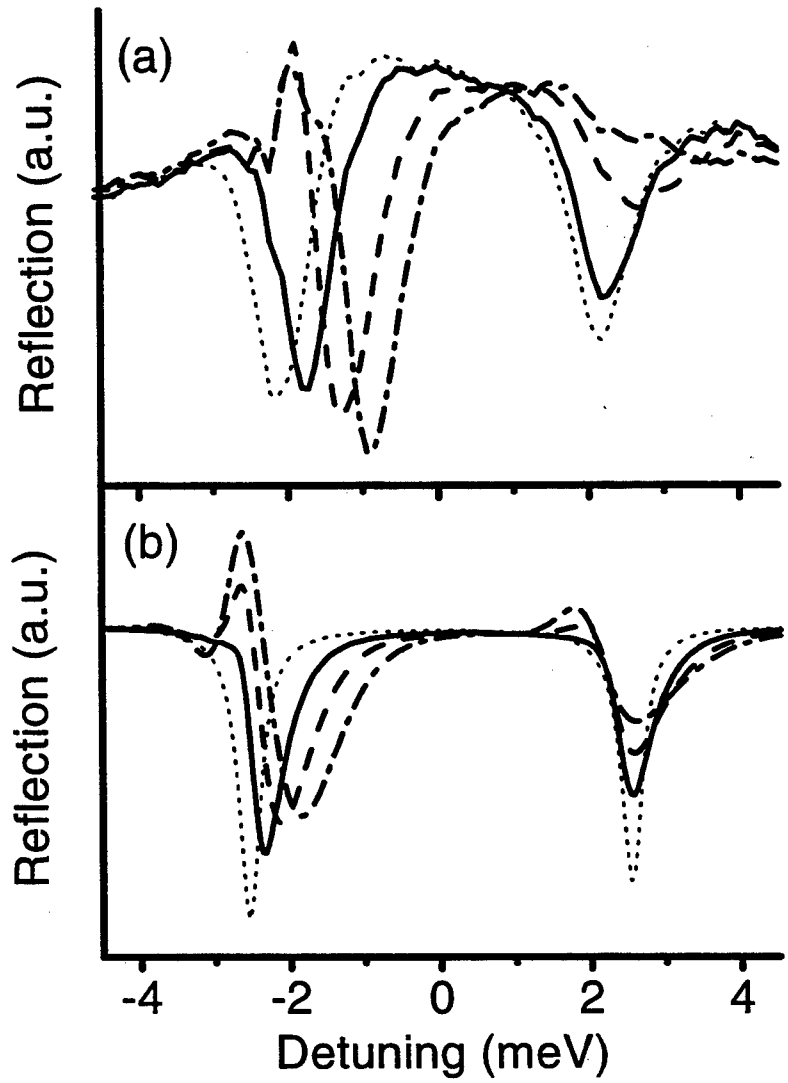

Fig. 1. (a) Experimental and (b) calculated reflection spectra of the polariton modes for different pump intensities and co-circular polarization when the detuning is 0.0 meV, and the pump pulse is centered at the lower mode.

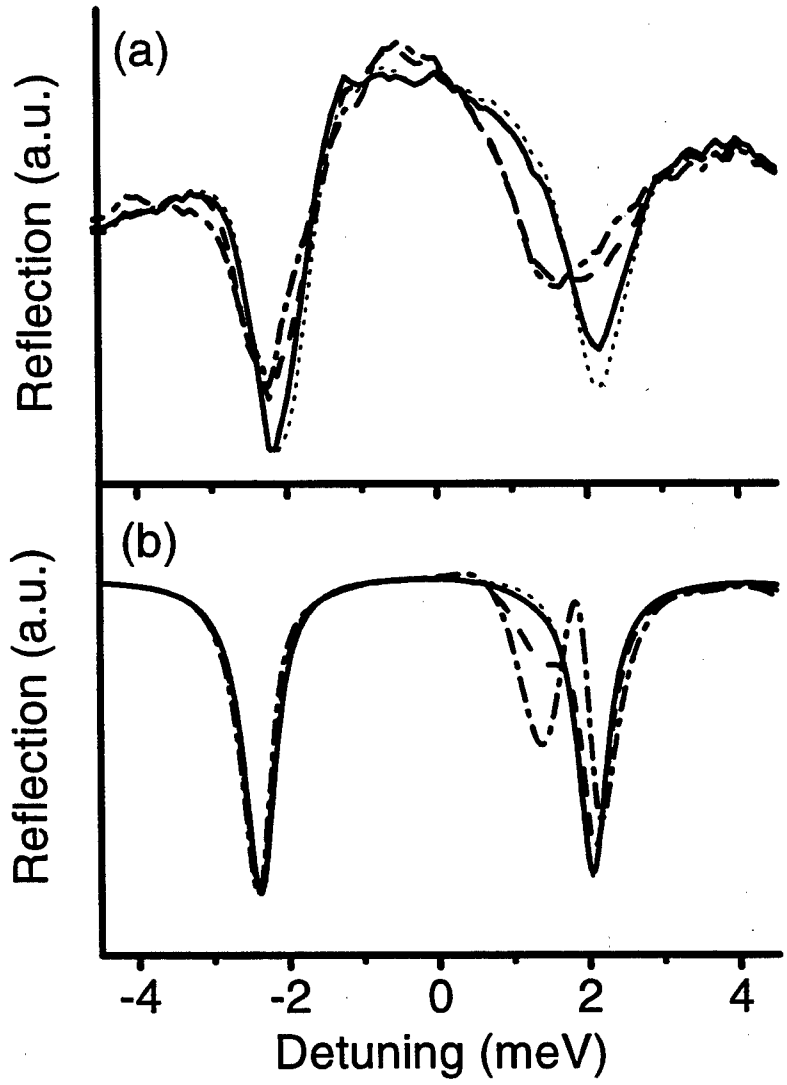

Fig. 2. Same as Fig. 1 for cross-circular polarization.

Enhanced optical/THz frequency mixing in a biased quantum well

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One of the basic operations required for all-optical information processing is the transfer of a data stream from one optical wavelength to another. The channel spacings in wavelength-division multiplexing (WDM) systems are in the order of a hundred GHz but can be larger if higher bit rates per channel become available. Thus, the exploration of possibilities of optical/THz mixing is very attractive for communication technology.

The optical/THz mixing is a process when two input signals, at the optical frequency ω and at the THz frequency Ω, produce an output (sidebands) at different optical frequencies $\omega \pm n\Omega$ with n an integer. Semiconductor quantum wells (QW) are very promising candidates as a medium where such a process can be realized. Indeed, the optical fields induce interband transitions while the THz field (polarized in the QW growth direction) can significantly modify the states within the conduction or valence band. A THz field which is in resonance with the intersubband transitions can lead to the splitting of the excitonic peaks with splitting linearly proportional to the THz field strength [1]. However, in a symmetric QW the optical sidebands are very weak for reasonable THz field strengths since the first-order optical/THz processes are forbidden by symmetry. This led to using asymmetric double QW structures to enhance the sidebands [2].

In our presentation we will focus on the possibility of applying a dc bias to a single QW to enhance the optical emission at the sidebands [3]. The process of the optical/THz mixing can be conveniently formulated as the interaction of the incident light with excitons dressed by the THz field. This allows one to find nonperturbative analytic expressions for the conversion efficiency of the fundamental to the THz sidebands. A maximum efficiency of a few percent is predicted for a single GaAs QW and ways for its further improvement will be outlined. Finally, we will discuss the possibility of coherently controlling the population of the excitons dressed by the THz field.

References:

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Heterojunction Interfacial Workfunction Internal Photoemission FIR Detectors for the THz Region

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Fast FIR detectors would find many uses in situations where the currently used bolometer detectors are too slow to allow desired measurements. In this work results are presented on a new detector concept that can be used for FIR detectors with much faster response than currently available bolometers. The detectors (see Fig. 1) consist of a sequence of highly doped GaAs emitter layers and undoped AlGaAs barrier layers. These Heterojunction Interfacial Workfunction Internal Photoemission (HEIWIP) detectors use free carrier absorption in a highly doped emitter region to generate carriers which then undergo internal photoemission at the heterojunction barrier. The emitted carriers are collected at a contact. The resulting detector has a lower dark current than a QWIP detector operating in the same wavelength range. In addition, the free carrier absorption is expected to remain relatively constant at larger wavelengths producing higher responsivities at these wavelengths than for QWIPs. HEIWIP detectors with response from 3 to 70 _m (100 – 4 THz) have already been fabricated and tested, with a responsivity of 11 A/W and D* = 1_10^{13} cm Hz- /W at 20 _m and 4.2 K (see Fig. 2). Based on 300 K background dark current the background limited performance (BLIP) temperature was estimated to be 15 K. The extension to longer wavelengths by lowering the workfunction (barrier height) at the heterojunction will be discussed. The response at selected wavelength ranges may be increased by employing cavity effects.

Supported in part by NASA and NSF.

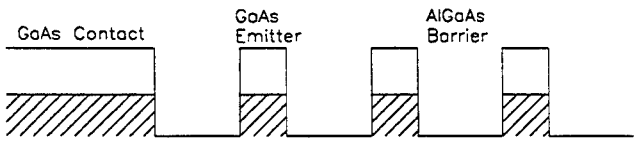

Fig. 1. Band diagram of a p-type HEIWIP detector.

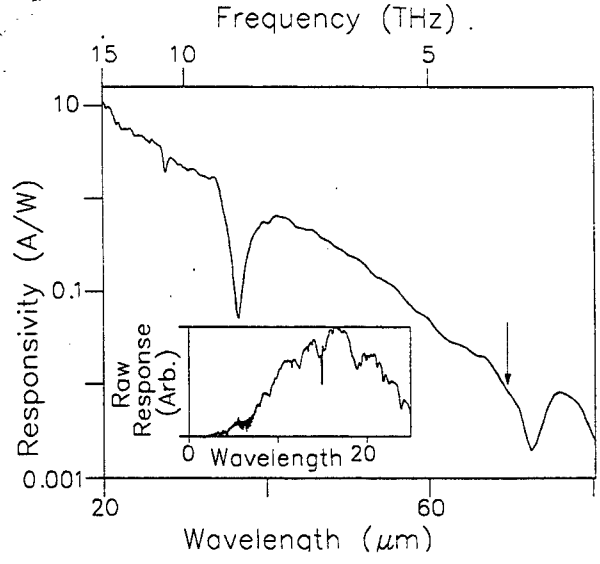

Fig. 2. Responsivity of the HEIWIP detector. The inset shows the raw response at shorter wavelengths.

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Optical resonant cavity effect in corrugated quantum well infrared photodetectors

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We report a resonant cavity effect in corrugated quantum well infrared photodetectors (CQWIPs). The corrugations are fabricated by etching V-grooves through the active region of QWIP to provide the total internal reflection of infrared radiation from the sidewalls. This allows the propagation of light parallel to the QWs with the electric field polarization perpendicular to the QWs to facilitate intersubband absorption and QWIP sensitivity to normally incident radiation (see Fig.1). The cross-sectional view of the fabricated CQWIP is shown in Fig.2.

Simulation of optical effects in CQWIPs has been done using finite-difference time-domain (FDTD) method. We have used FDTD simulator EMLAB (ISE Systems Eng., Inc.), which allows solving the time-dependent Maxwell equations in 2D and 3D geometries. The initial conditions specified the plane monochromatic wave incident from the substrate, and the simulations proceeded until a steady-state solution is obtained. The optical intensity, defined as $I=\langle E_y^2 \rangle$ (E_y is the vertical component of the electric field), was integrated over the active (QW) region of CQWIP to characterize the optical coupling efficiency. Figure 3 shows the calculated total optical intensity for CQWIP with 0.5 μm-thick substrate. Intensity shows a resonant behavior as a function of the wavenumber, which is explained as follows. After reflection from the sidewall, light propagates parallel to the QW plane, and then downwards after the reflection from the other sidewall. A part of light is reflected back to the substrate at the substrate/air interface, and follows the path described above. Thus, the propagation of light in CQWIP with 45-degree sidewalls is similar to that in resonant-cavity enhanced photonic devices with two parallel interfaces. An analysis shows that the thickness of the resonant cavity is L=H+b, where H is the CQWIP height (including substrate), and b is the half-width of the top of the pyramid. This thickness is equal to the half of the length of the light pass due to the interference between the light rays incident on the opposite sidewalls. The resonance condition is described by the formula $2\beta L+\psi_1+2\psi_2+\psi_3=2m\pi$, where $\beta=2n\pi\lambda_0$ is the propagation constant, λ_0 is the wavelength of light in vacuum, and ψ_1, ψ_2, ψ_3 are the phase shifts due to light reflections at the substrate bottom, sidewall, and the symmetry plane, respectively. The spacing between the modes is given by $\Delta k=\Delta(1/\lambda_0)=1/(2nL)=1/[2n(H+b)]$, where n is the index of refraction of the CQWIP material. This simple analytical model is confirmed by results of numerical simulation of CQWIPs with different structural parameters (substrate thickness, width of the pyramid, etc.). Simulations of CQWIPs with "imperfect" geometry (non-45 degree sidewalls, "warped" sidewalls, etc.) show that the optical cavity effect is still present in those structures. Experimental data on CQWIP responsivity confirm the optical resonance effect. These results have important implications for optimization of CQWIP design, especially for applications involving coherent sources of infrared radiations.

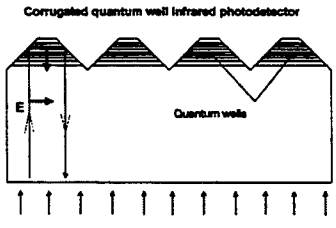

Fig.1. Schematic diagram of CQWIP.

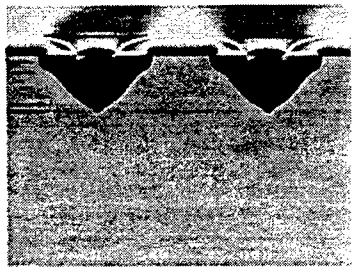

Fig.2. Cross-sectional view of fabricated CQWIP.

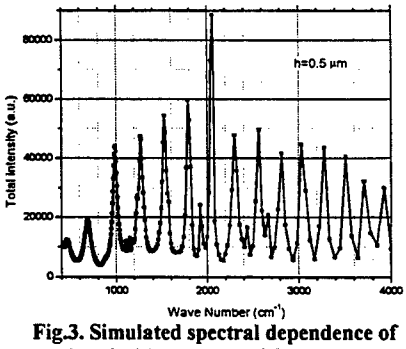

Fig.3. Simulated spectral dependence of total optical intensity in CQWIP.

Photons confined in 3D-microcavities doped with quantum dots

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We present the concept of a complete three-dimensionally confined photonic dot (PD) doped with CdSe quantum dots (QDs). The QDs@PD-structures have been prepared using hollow polymer microspheres doped with CdSe QDs or very small glass spheres covered with a thin polymeric shell containing QDs. With R<5 μm, the small size of the PD ensures a large mode spacing of a few tens of meV, comparable or even larger than the emission linewidth $\hbar\Delta\omega_{QD}$ of a single CdSe QD. For the cavity mode widths $\hbar\Delta\omega_{cav}$, values between 250 μeV and 1.5 meV were observed yielding maximum Q-factors ≥7500 measured at room temperature. The coupling of a single CdSe nanocrystal to a single cavity mode is achieved and first hints to a control of spectral diffusion within a cavity have been obtained. Using imaging spectroscopy at the diffraction limit, the emission spectra are analyzed and intensity and polarisation are mapped accross a single microsphere. The experimentally obtained polarisation-dependent mode images confirm the calculated mode assignment. Polarisation-selective detection schemes allow a spatial addressing of nanocrystals at the surface of the cavity exploiting the lifting of degeneracy of TM and TE-modes in a spherical cavity. Since a QD@PD structure is a very promising object to design an optically pumped QD-based microlaser emitting in the visible spectral range at room temperature, the changes in the emission characteristics of a QDs@PD system have been studied when both the number of QDs and the pump intensity is gradually increased. For a low-Q cavity (Q~2000), mode-narrowing and a threshold-behaviour in the intensity-dependent emission characteristics is observed, as well as mode competition which indicates the onset of lasing (T=300K, emission at ~600 nm). At low temperatures and homogeneous linewidths of single quantum dots as narrow as the photonic dot modes, we observe an enhancement in the spontaneous emission rate, i.e. the Purcell effect is found for quantum dots inside a photonic dot. For these studies we use two special samples: one is a high-Q glass microsphere, the other a small piece of glass from a broken microsphere. Both are impregnated with CdSe QDs in the same process, thus eliminating all variations arising from chemical preparation. To avoid the influence of nonradiative recombination caused by trap processes we optimized before the preparation route and used only those nanocrystals which exhibit monoexponential decay curves with lifetimes in the range of nanoseconds. The PL-decay times have been studied spectrally resolved, in- and off-resonant to cavity modes. Enhancement factors of the spontaneous emission rate in the 3D-cavity compared to emission in free space varying between 2 and 6 have been obtained.

Resonant Nanocavities in Two-Dimensional Photonic Crystals

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Summary

A Fabry-Perot resonant cavity can be formed in a distributed Bragg mirror or 1-D photonic crystal by introducing one or more defects into the periodic structure. In a similar fashion, a resonant nanocavity can be created in a two or three dimensional photonic crystal structure. We analyze a periodic array of 2-D resonant cavities formed by introducing defects into a three-material 2-D photonic crystal [1,2], and investigate the near-field distribution inside the nanostructure, as well as the transmission properties of the filter as a function of wavelength and incidence angle.

A schematic diagram of 2-D three-material a photonic crystal with periodic defects is shown in Fig. 1. A defect, consisting of a perturbation of the refractive index of the material in the central layer of the structure, is introduced into every fifth period of the photonic crystal. For normally incident monochromatic illumination at the resonance wavelength, Fig. 2 shows the near-field distribution inside one period of nanostructure. As with a Fabry-Perot resonant cavity, there is an extremely strong field localized at the site of the defect, which may, for example, be used to the enhancement of detection efficiency or a nonlinear optical process.

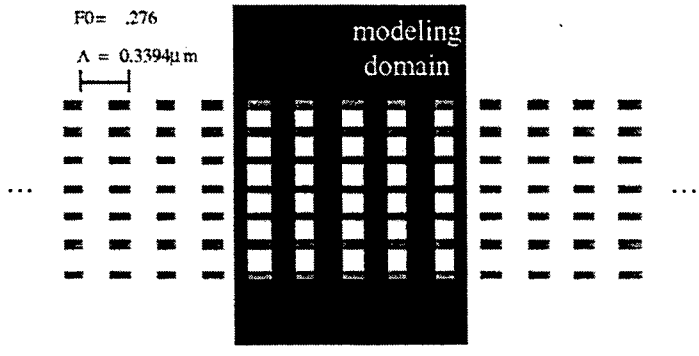

Fig. 1. Schematic diagram of the array of nanocavities formed by introducing refractive index defects every fifth period in the center layer of a 2-D photonic crystal structure.

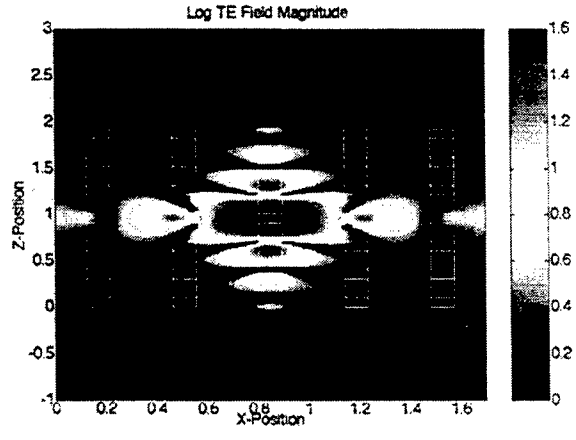

Fig. 2. Near-field distribution inside one period of the 2-D resonant cavity nanostructure with normally incident monochromatic illumination at the resonance wavelength.

The transmittivity versus incidence angle and wavelength for this structure without and with the defects are shown in Figs. 3a and 3b, respectively. Fig. 3a shows the bandgap of structure, while Fig. 3b shows that the introduction of the periodic defects produces a resonant cavity, permitting a narrow range of wavelengths within the bandgap to be transmitted. Due to the 2-D nature of the structure, the resonant wavelength is uncoupled from the

incidence angle, yielding an angularly insensitive wavelength filter. We also analyze the effect of the defect spacing, defect refractive index, and number of photonic crystal layers on the nanocavity resonance to engineer the performance characteristics of the filter.

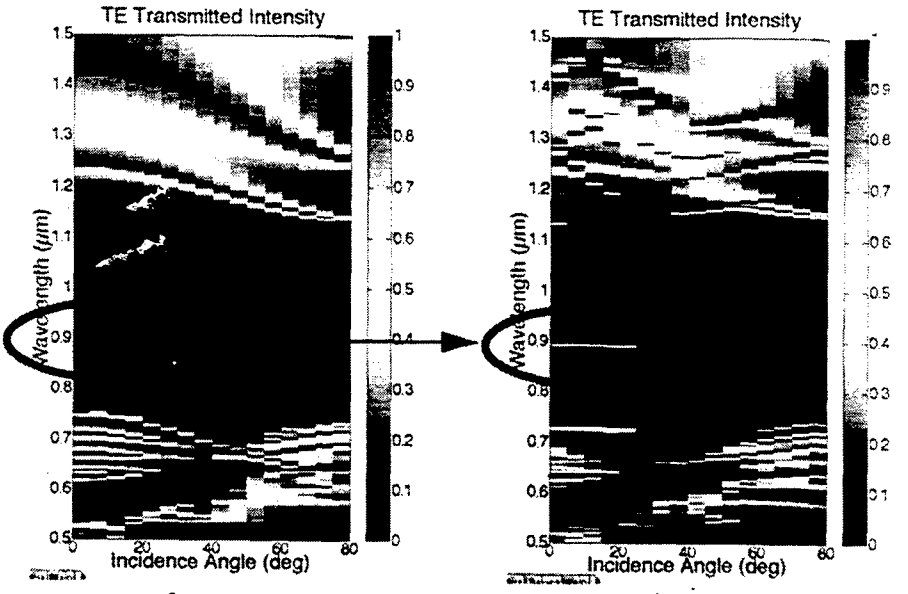

Fig. 3. Transmittivity as a function of incidence angle and wavelength of (a) a 2-D photonic crystal without defects and (b) a filter structure similar to that shown in Fig. 2. The introduction of the periodic defect permits transmission of a narrow range of wavelengths for a wide range of incidence angles.

To accurately investigate the near-field properties of optical nanostructures, we apply the well-established Rigorous Coupled-Wave Analysis (RCWA) technique [3,4], modified for computation and visualization of the internal and near fields. This tool enables the rigorous near-field electromagnetic design and analysis of a wide range of periodic optical nanostructures.

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Microcavity-enhanced $\chi^{(2)}$ Nonlinearities in Semiconductor Waveguides: Surface-Emitted Second-Harmonic Generation in the Subpicosecond Regime

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Surface-emitted second-harmonic generation (SESHG) in semiconductor waveguides [1] offers a unique means for ultrafast optical signal processing in a simple, integrated, nonlinear optical waveguide. Indeed, it is possible to exploit the large $\chi^{(2)}$ nonlinearity of GaAs by providing for quasi-phase matching in the growth direction. When employed with ultrafast optical pulses however, the interaction length of the fundamental pulses is dramatically reduced severely limiting the applicability of such structures.

We have incorporated an integrated microcavity into a GaAs/AlGaAs optical waveguide structure with vertical quasi-phase-matching, and have realized a SESHG device that significantly enhances the efficiency for optical pulses in the subpicosecond regime. We demonstrate both theoretically and experimentally that nonlinear interactions involving short optical pulses can be enhanced by a microcavity, even when the resonance width is substantially narrower than the spectral content of the optical pulse. Applications of such devices include integrated correlators [2], spectrometers [3], and serial-to-parallel converters for time-division demultiplexing [4].

We developed a theory to predict the cavity enhancement based on the temporal duration of the fundamental pulses and on the semiconductor structure. The frequency-dependent enhancement is obtained via a Fabry-Perot-like analysis, and integration in the frequency domain provides the final effective enhancement factor. This approach enables us to define design guidelines for SESHG structures.

The generic multilayer AlGaAs waveguide structure is shown in Fig. 1, along with the rear-facet reflection geometry used to measure the nonlinear efficiency. Several nonlinear efficiency measurements were performed using microcavities with different finesse. The measured and calculated enhancements are plotted as a function of top mirror reflectivity and single-pass cavity losses (αd) in Fig. 2. As expected, the efficiency increases with cavity finesse until the filtering of the broad pulse spectrum outweighs the enhancement at the resonance. We note that in the absence of intracavity losses, the enhancement at the resonance always dominates over the filtering effect, and it is therefore advantageous to make the reflectance as high as possible. However scattering or residual band-to-band absorption loss limits the achievable enhancement and represents a critical parameter for the performance of the resonant cavity.

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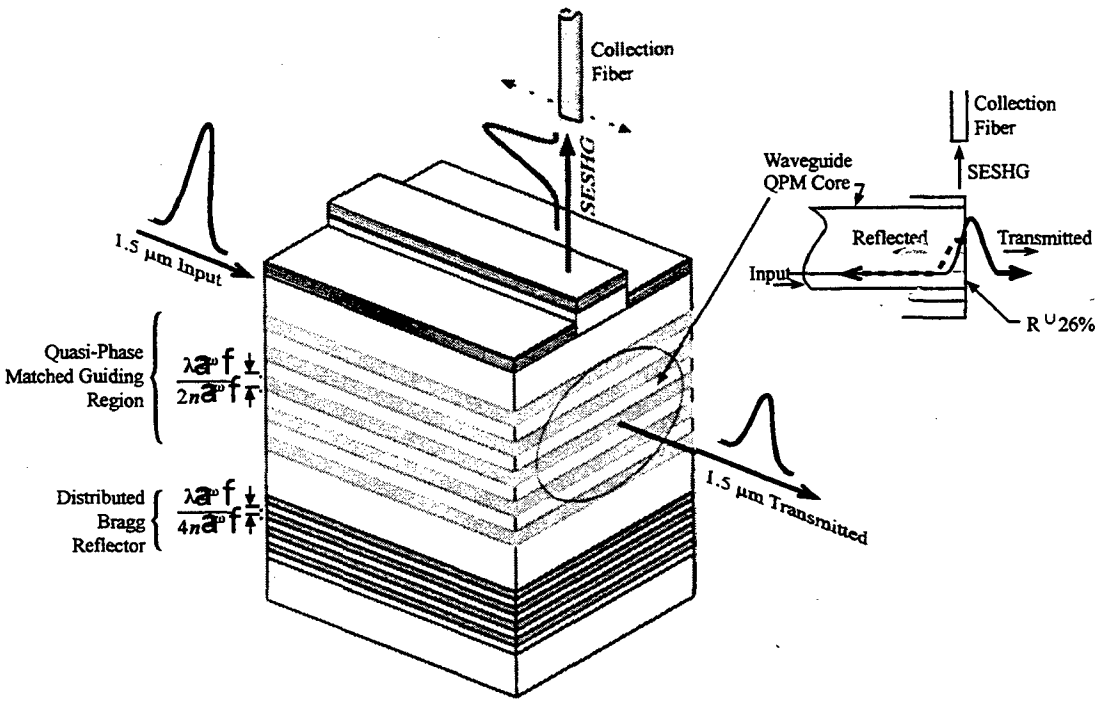

Fig. 1: Device structure and rear-facet geometry.

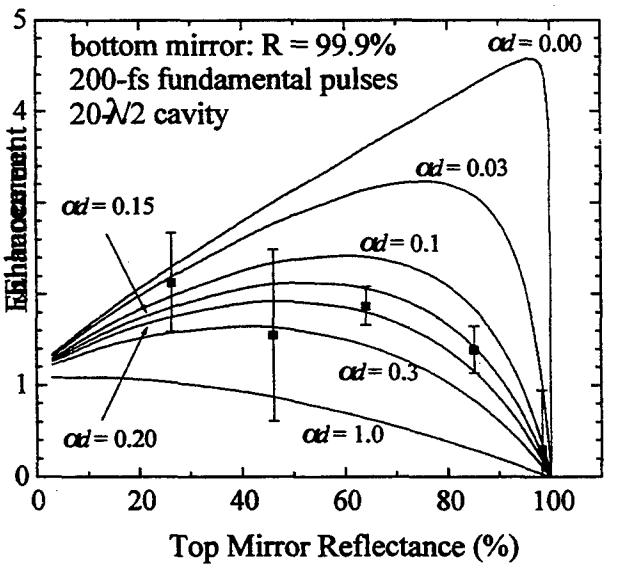

Fig. 2: Enhancement as a function of top mirror reflectance and intracavity loss.

Dimensional dependence of interband two-photon transition in perovskite copper oxides

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Strongly correlated electron (SCE) systems show many exotic transport and/or magnetic phenomena, such as high- temperature superconductivity and colossal magnetoresistance. Large electron-electron correlation energy manifests itself in optical properties of SCE systems as strong two-photon absorption (TPA) with picosecond recovery of optical transparency, which has been recently found in a quasi-one-dimensional (1D) perovskite copper oxide (cuprate) Sr_2CuO_3 [1], and giant electro-reflectance observed in 1D Mott insulators [2]. Since the Cu-O network geometry varies extensively within cuprate family, the cuprates are well-suited materials to investigate the dimensionality dependence of the optical nonlinearity in SCE systems. To clarify the microscopic mechanisms of the strong TPA in the 1D cuprate, we perform sub-picosecond pump-probe measurements in 1D and 2D cuprates. We observe clear difference in the pump-induced transmission change in 1D and 2D systems: The 2D system shows slower (~ 30 ps) recovery as well as picosecond one and an order of magnitude smaller TPA than that of the 1D system. Cluster calculation with 2-band extended Hubbard model qualitatively explains the experimental results.

Since the mechanisms of the strong optical nonlinearity and the ultrafast recovery in the 1D cuprates are completely different from those in conventional band insulators, this 1D system constitutes a new and promising class of materials for ultrafast optoelectronics. Performing Z-scan measurements, we examine the potential of the 1D cuprates as materials for all-optical switching (AOS) applications [3]. We show that around 1.6 μm the intensity dependent refractive index $n_2 \sim 10^{-12}$ cm^2/W of Sr_2CuO_3 at room temperature is comparable with that of polydiacetylenes [4], which is known to show the largest half-gap optical nonlinearity. The application potential of this material in AOS devices is discussed.

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Optical Stark effect in an inorganic-organic layered perovskite compound, $(C_6H_5C_2H_4NH_3)_2PbI_4$

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Ultrafast absorption change induced by a light pulse below the exciton resonance has been interpreted in terms of optical Stark effect. Combescotes [1] predicted that red-shift of the exciton resonance would be observed if the biexciton state is stable. So far, only a few examples are reported: First on a CuCl film [2] and recently on InGaAs quantum well [3].

In this paper, we report optical Stark shift of the exciton resonance in an layered perovskite compound, $(C_6H_5C_2H_4NH_3)_2PbI_4$ (abbreviated as PEPI). PEPI is a layered semiconductor in which perovskite PbI_4 monolayers are sandwiched by organic layers. The lowest exciton is strongly confined in the PbI_4 layer. Biexciton binding energy has been found to be 45 meV [4]. To study the optical Stark effect in PEPI, we have measured transient absorption spectra of PEPI films at 5 K pumped below the exciton resonance. The time resolution was 200 fs.

Figure 1 (a, b) shows the differential absorption spectra with the co-circular and the counter-circular polarization configurations at the zero delay time between the pump and the probe pulses. The pump energy is 2.29 eV, which is 65 meV below the exciton resonance at 2.355 eV. It is found that the exciton resonance shifts to the blue and the red in the co-circular and the counter-circular polarization configurations, respectively. This polarization dependence is straightforwardly understood in terms of the interaction between a virtual exciton produced by the pump pulse and a real exciton produced by the probe pulse.

Figure 1 (c, d) shows the differential spectra with the co-linear and the cross-linear polarization configuration, respectively, at the zero delay time. It is found that the exciton resonance is broadened in the co-linear configuration and is shifted to the blue in the cross-linear configuration. This broadening is different from those observed in CuCl nor InGaAs QWs. This polarization dependence is presently under consideration.

In PEPI, it seems that optical Stark shift occurs with rather high efficiency. The optical density change due to the optical Stark effect amounts to 25 % of the change caused by pumping just at the exciton resonance with the same intensity. This high efficiency may be attributed to the large exciton oscillator strength and the presence of stable biexcitons by virtue of the dielectric confinement by the organic layers.

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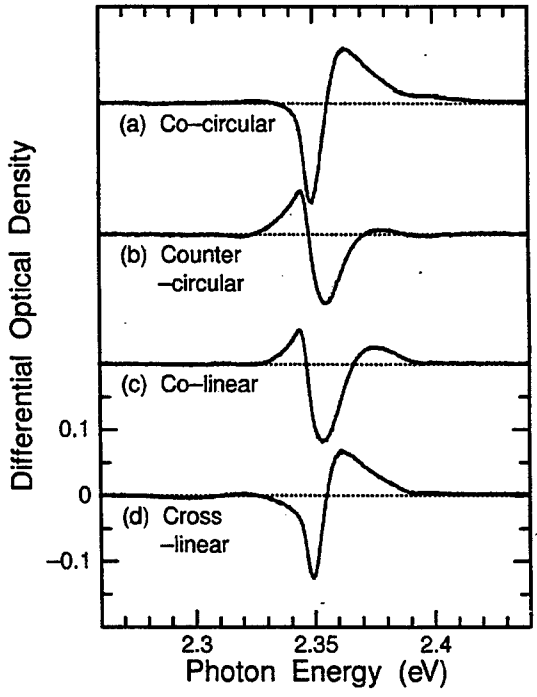

FIG. 1. Differential Absorption spectra of PEPI film at 5 K, pumped at 2.29 eV with an intensity of 50 μJ/cm².

Origin of second harmonic generation from photonic crystal slabs.

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It is generally believed that efficient second harmonic generation (SHG) is possible only if the inversion symmetry is missing in the crystal structure. Amorphous materials have never been the candidates in this context. However it may be meaningful to think about the length scale of inversion symmetry that is required to generate SHG, since we can now endow materials with artificial structures using advanced nanofabrication techniques. In this paper, we report that in a periodic structure of the order of light wavelength the inhomogeneous field distribution can generate sizable second harmonics even if the constituent materials have inversion symmetry.

Rectangular one-dimensional grating structure is fabricated on quartz substrates by means of electron beam lithography. Several gratings of pitches around 700nm were fabricated on a substrate. In order to enhance SHG efficiency a centrosymmetric semiconductor $(C_6H_5C_2H_4NH_3)_2PbI_4$ (referred to as PEPI hereafter) was imbedded into grating grooves by spin-coating its acetonitrile solution. Polystyrene was overcoated on the top in order to support guided waves in the sample. The fourth Bragg resonance is in the range of excitonic resonance of PEPI at 2.4 eV. Strong coupling between the exciton and the quasi-guided wave has been investigated in such structures [1].

Near infrared nanoseconds light pulses from an optical parametric oscillator are sent into the sample and transmitted light was spectrally analyzed in the visible range after a $CuSO_4$ band-pass filter. We observed the SHG emission when the sample is tilted to the periodic axis so that the incident angle matches to the generation of quasi-waveguided modes in the infrared region. The SHG intensity was comparable to that from GaAs bulk crystal that lacks inversion symmetry. By tuning the incident wavelength, we measured the SHG intensity at the matching angles. Importantly we found that the SHG intensity vanishes when the matching angle is 0. It suggests that the uneven distribution of the light field is responsible for the SHG. The experimental result will be compared to the field distribution calculated by means of the scattering matrix method [2].

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Theoretical study on second-order nonlinear optical response due to mesoscopic breakdown of inversion symmetry

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It is well known that only those crystals without the inversion symmetry in their crystal structures possess the second-order nonlinearity, and that those crystals with inversion symmetry do not possess it except for surfaces and interfaces where inversion symmetry is lost on microscopic scales. On the other hand, owing to the recent technological progress of preparing the fine-structured materials, we can now realize such systems that have inversion symmetry on microscopic scales (of atomic distances), but the symmetry is lost on mesoscopic scales (of the wavelength of light). In such systems, if the electronic wavefunctions extend over the whole system, electrons can suspect such breakdown of inversion symmetry on mesoscopic scales, so even the electrons in the bulk part of the crystal may contribute to the second-order nonlinearity.

We theoretically investigate the second-order nonlinear optical response due to such mesoscopic breakdown of inversion symmetry. To this end, we employ a single free electron confined in a two-dimensional cluster (quantum dot) on x-y plane, and investigate its second-order nonlinear response to an electromagnetic wave propagating along z-direction (see Fig. 1), which is characterized by the second-order polarizability $\beta_{ijk}^{(2)}(\omega+\omega)$ ($i,j,k=x,y$). The free electron in a cluster is described by one-band tight-binding Hamiltonian.

There are two factors in this system that determines the second-order optical response: the size and the shape of the cluster. First, in order to see the size dependence of $\beta_{ijk}^{(2)}(\omega+\omega)$, we fixed the cluster shape for example at an equilateral triangle and change only the cluster size L. It is confirmed numerically that $\beta_{ijk}^{(2)}(\omega+\omega)$ is proportional to L^{-3} (see Fig. 2), which is also explained in an analytic manner. As for the cluster shape, it is indispensable for existence of nonzero $\beta_{ijk}^{(2)}(\omega+\omega)$ that the cluster shape does not have inversion symmetry. We show the growth of $\beta_{ijk}^{(2)}(\omega+\omega)$ as we gradually break the inversion symmetry starting from an inversion-symmetric shape.

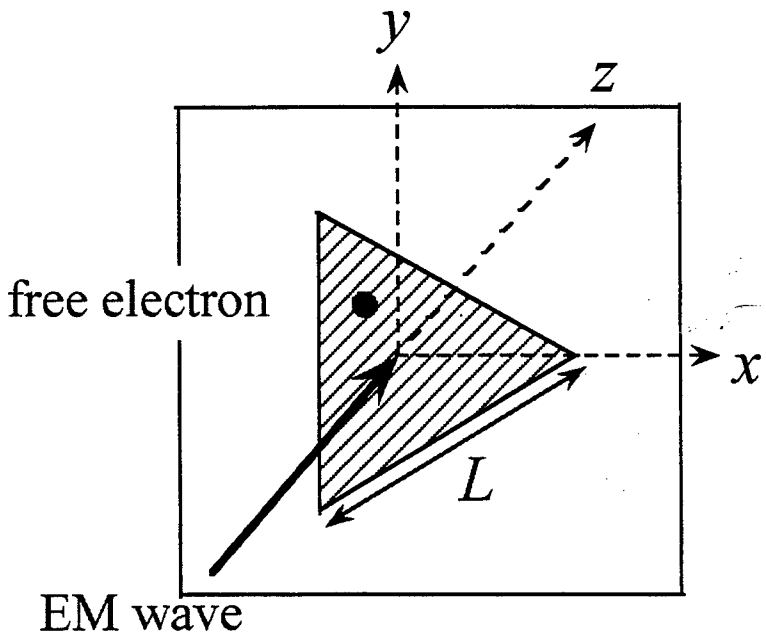

Fig. 1: Schematic view of the situation considered in this study. A free electron is confined in a two-dimensional cluster on *x-y* plane, and an electromagnetic wave is applied perpendicularly to it.

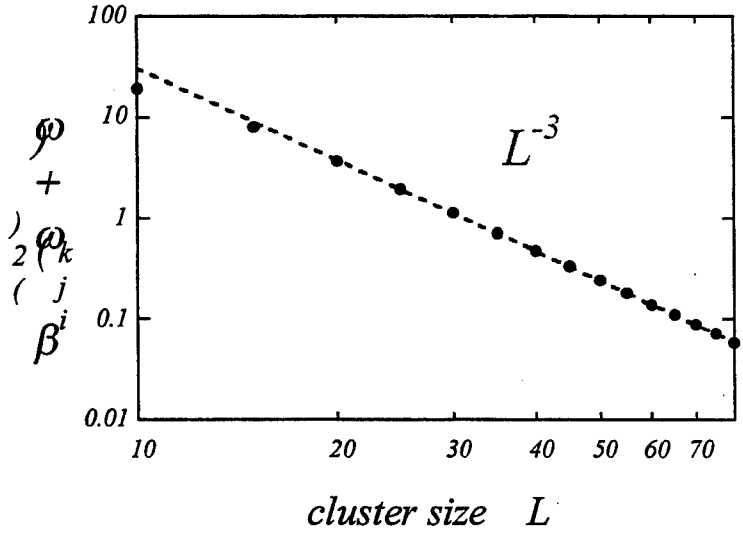

Fig. 2: The cluster size (L) dependence of the second-order polarizability $\beta_{ijk}^{(2)}(\omega+\omega)$. Numerical results (dots) are confirmed to be proportional to L^{-3} (broken line).

MEMS based on Casimir Forces

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We present a new class of MicroElectroMechanicalSystems (MEMS) in which the Casimir force between metallic surfaces at submicron distances has been exploited for the quantum mechanical actuation and for the realization of a new class of nonlinear bistable oscillators.

The Casimir force is the attraction between uncharged metallic surfaces due to quantum mechanical vacuum fluctuations of the electromagnetic field. We demonstrate the Casimir effect in microelectromechanical systems (MEMS) using a micromachined torsional device. Attraction between a polysilicon plate and a spherical metallic surface results in a torque that rotates the plate about two thin torsional rods. The dependence of the rotation angle on the separation between the surfaces is in agreement with calculations of the Casimir force. These results show that quantum electrodynamical effects play a significant role in MEMS when the separation between components is in the nanometer range.

We have also demonstrated that the Casimir effect has a profound influence on the oscillatory behavior of MEMS when surfaces are in close proximity (≤100 nm). Frequency shifts, hysteretic behavior and bistability are observed in the frequency response of a periodically driven micromachined torsional oscillator due to the nonlinear dependence of the Casimir force on distance. Our measurements also show that this device can be utilized as a high sensitivity position sensor.

The topological nature of the Casimir force and of the more general Lifschitz force between macroscopic bodies opens the door to the design of the latter forces by suitable control of the boundary conditions of the electromagnetic fields in MEMS and to many applications.

Excitonic radius in the cavity polariton in the regime of very strong coupling

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We consider the case of very strong coupling in semiconductor microcavity exciton polariton, i.e. when the Vacuum Rabi splitting energy becomes comparable to the exciton binding energy. In this case, one cannot treat the electron-photon interaction as a perturbation to the exciton Hamiltonian - both Coulomb attraction and cavity interaction should be treated together. We develop a very simple variational model that shows that the binding energy and excitonic radius of the exciton-polariton change significantly in the very strong coupling mode.

The excitonic radius change is manifested by significant changes in the oscillator strength - increase in the oscillator strength for the lower polariton branch and increase for the upper one. This result is in agreement with experimental data.

We also show that coupling with photons can "restore" the exciton in the strongly screened environment, precluding the Mott transition. Another interesting implication of the very strong coupling is that elliptical excitons can be observed for off-axis excitations.

From semiconductor microcavities to photon crystals

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Recent joint experimental and theoretical work involving semiconductor microcavities will be discussed. Micron-sized, laterally structured microcavities have been fabricated by lithography of planar structures. Experimental studies are made using photoluminescence spectroscopy, and numerical calculations are done with a boundary element method developed for photon systems [1]. Single cavities are shown to exhibit sharp, well-confined photon modes in the optical regime analogous to the electronic states of quantum dots [2]. Angle resolved studies permit the measurement of the electric fields of the modes. The exciton-photon interaction, which is measured by the Rabi splitting, is found to depend on cavity size. Coupled pairs of microcavities are shown to exhibit a rich pattern of photon modes analogous to the bonding and antibonding electronic orbitals of molecules [3]. Photon band gaps emerge in chains with increasing numbers of microcavities. These chains exhibit band gaps out to the fourth Brillouin zone boundary [4], and the magnitudes of the gaps depend on the coupling between the cavities. Defect cavities have been introduced into the linear chain systems, and their energies are tuned in the gap by defect cavity size. Splittings of linearly polarized modes in asymmetric cavities have been demonstrated, and it has been shown that magnetic fields transform them into circularly polarized modes. Cavities are shown to enhance on-resonance emission from quantum dots by up to a factor of five and to suppress off resonance emission by up to an order of magnitude [5]. Experimental results are in agreement with calculations for these systems. These systems provide a unique opportunity to study the physics of confined photon modes in the optical regime in detail and to explore opportunities for their technological exploitation. This work is of interest in connection with issues ranging from improved lasers to implementations for quantum computation.

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Ultrafast Dynamics of the Electron Gas

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In undoped semiconductors, the ground state excitations have high energy, of the order of the bandgap. As a result, the e-h pairs behave as exciton quasiparticles, and many--particle correlations can only be dynamically generated by the optical excitation. This simplifies the problem of calculating the ultrafast nonlinear optical dynamics, and all interaction processes that contribute to a given order in the optical field can be included. However, if a degenerate Fermi sea is already present in the system prior to the optical excitation,the standard analysis needs to be revisited. This is the case, for instance, in a modulation doped quantum well, where a two dimensional electron gas exists in the sample, which can be polarized and excited via nonlinear optical processes. As a result, a photoexcited exciton is dressed by low--energy electron gas excitations, and the characteristic time scales of such interacting processes are within the resolution of currently available optical pulses.

The presence in the ground state of low energy excitations able to interact with the photoexcited carriers raises formidable theoretical difficulties. Although the role of such interactions during the thermalization stage is relatively understood, much less is known about the important coherent regime. In this talk we will briefly review recent efforts for describing such effects [1-4]. We will focuss, in particular, on non--Markovian memory effects in the coherent ultrafast nonlinear optical spectra that result from the charge and spin correlations between the photoexcited and electron gas carriers.

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Coherence and Exciton-Exciton Interactions: Applications to All-optical Polarization Switching

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In recent years, we (and others) have expended a great deal of effort to measure the polarization dynamics of the coherent emission from quantum wells. In that work, we have demonstrated that the polarization state of the coherent nonlinear emission varies dramatically and systematically with input polarization, that these polarization dynamics are particularly sensitive to many body effects and that they can be used to delineate the roles of various exciton-exciton interactions. Initially, our efforts focused on measuring the polarization dynamics of the signal in the background-free direction (or so-called $2\mathbf{k}_2\text{-}\mathbf{k}_1$ direction) in a standard two-beam four-wave-mixing geometry. More recently, however, we have investigated the polarization dynamics of the coherent emission in the probe direction (or $\mathbf{k}_2$-direction). In the $\mathbf{k}_2$-direction, the signal consists of the transmitted portion of the probe and the linear and nonlinear coherent emission. The coherent emission in the probe $\mathbf{k}_2$-direction is fundamentally different from that in the $2\mathbf{k}_2\text{-}\mathbf{k}_1$ direction, and the natural self-heterodyning of the transmitted probe and the coherent emission allows the measurement of phenomena that can not be detected in the more conventional $2\mathbf{k}_2\text{-}\mathbf{k}_1$ direction. We shall review these differences. More importantly for our discussions here, however, is the fact that this latter geometry is the same as that used to construct prototype all-optical polarization switches. Here, we shall describe novel ways that coherence effects and many-body interactions can be used to construct polarization switches and the ways in which such phenomena affect existing switches.

For example, most *resonant* optically-addressed switches are based on the *incoherent* nonlinear response of the material. That is, the interband dephasing time for the optically-generated carriers is short compared to the switching time. Here, we will describe a polarization switch that is based on the *coherent* nonlinear response of unstrained quantum wells, where the underlying mechanisms are the coherent exciton-exciton interactions. Consequently, the turn-on and turn-off times of this coherent switch are determined by the dephasing time and are in the fs regime. Nevertheless, this is a resonant device, and, even though the carriers do not restrict the switching times, they still accumulate until they recombine (~ns) or are swept out.

We shall also discuss the role of dephasing processes in determining the turn-on and turn-off times of all-optical polarization switches based on the resonant excitation of spin-polarized electrons. Devices based on the spin degree of freedom have become fashionable of late, and spin switches have been demonstrated with turn-off times in the ps regime. We will show that dephasing processes mitigated by many-body interactions limit the turn-on time in spin switches and provide a source for an initially rapid sub-ps turn-off, but complete turn-off requires spin relaxation. As with other resonant devices, however, complete recovery requires either carrier recombination or sweep out.

Finally, we will describe an optically-addressed polarization switch that is based on the *near-resonant* excitation of *spin-polarized* "virtual excitons". By operating near (but below) resonance, we achieve nonlinearities that approach the magnitudes of those that can be obtained with resonant excitation, yet we are able to avoid the restrictions that accompany carrier generation, and we take advantage of speeds that are characteristic of non-resonant excitation.

The Dark Side of the Cherenkov Effect: Light Emitting Light at Subluminal Speeds

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As shown by Auston and co-workers [1], an ultrafast pulse moving in an electro-optic medium produces Cherenkov radiation (CR) if its group velocity, c_g, is greater than the phase velocity of light at infrared frequencies. The pulse generates a low-frequency polarization as it interacts with itself through a $\chi^{(2)}$-process and, in so doing, it behaves as an optical analog of a relativistic dipole. For a point particle, the radiation is emitted in a cone with the characteristic Cherenkov angle $\theta_C = \cos^{-1}(c_0/c_g)$, where $c_0 = c/n_0$ and n_0 is the low-frequency index of refraction. Here, we demonstrate new and unexpected features of CR resulting from optical dispersion. Contrary to the common understanding, we identify conditions for which CR is emitted at subluminal but not at superluminal speeds, and we verify this prediction in pump-probe experiments on ZnSe. We also present calculations for a point source revealing that an arbitrary cone angle is actually associated with two velocities, one above and one below a certain speed threshold. Finally, we argue that CR due to optical nonlinearities and phase-matched excitation of phonon polaritons by ultrafast pulses [2] are the same physical phenomenon.

Pump-probe measurements were carried out at 10K using a laser system that produces 90 fs pulses in the range 1.8-2.3 eV by pumping an OPA with a Ti:sapphire regenerative amplifier at 200 kHz. In the operating range of our OPA, the dispersion in ZnSe is sufficiently large that, above ~ 2 eV, the group velocity becomes smaller than the phase velocity of light at zero frequency, c_0. Differential transmission traces reveal oscillations with frequency Ω that disappear if $c_g > c_0$ and for which $d\Omega/dc_g < 0$. This behavior is consistent with CR due to a planar distribution of dipoles [3]. In this case, it can be shown that the phase matching condition is $q \approx \Omega/c_g$. The c_g-dependence of Ω reflects simply the fact that the polariton group velocity decreases with increasing q.

Calculations of the Cherenkov field for a point particle using the parameters for ZnSe reveal that θ_C is well defined not only at superluminal but also at subluminal speeds. More importantly, our results generally indicate that the behavior of the angle is non-monotonic in that a given θ_C is connected not with one but with two particle velocities, one below and one above the light threshold at c_0.

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Theory of Resonant Secondary Emission

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The issue of quantum coherence and coherence loss is a central question studied in many ultra-fast optical experiments. We discuss several recent developments in this field — focussing on semiconductor quantum wells, which are the most widely considered model systems. Electronic coherence in the sample is best studied by measuring the coherence of the radiation emitted after a short pulsed excitation. Following the specular instantaneous response (transmission, reflection), radiation is emitted in any spatial direction. It comprises Rayleigh scattering and photoluminescence and it will be called secondary emission, henceforth.

A theory of secondary emission has to include both resonant and off-resonant emission, and elastic scattering (typically by disorder due to rough heterointerfaces) as well as inelastic scattering (at low temperature, predominantly due to acoustic phonons) [1]. We found the density-matrix formulation to be best suited within the present framework. A careful distinction between the average over the observation angle (ensemble average) and the quantum mechanical average over pulse repetition ("history") is necessary for the interpretation of experiments which measure coherence by Michelson interferometry or using speckle statistics. Based on numerical solutions of the exciton center-of-mass Schrödinger equation for eigenfunctions ψ_α and eigenenergies ϵ_α and with numerically obtained phonon matrix elements, predictions for macroscopic spectra and for statistical properties of spatially resolved spectra were obtained.

The coherently scattered signal is determined by the energy-level correlation weighted with optical matrix elements $M_\alpha(\vec{k}) \sim \int d^2\vec{R}\, \exp(i\vec{k}\cdot\vec{R})\psi_\alpha(\vec{R})$ [2],

$$R_c(\hbar\omega) = \Omega^{-1}\overline{\sum_{\alpha\beta} M^*_\alpha(\vec{k}_{\rm in})M_\alpha(\vec{k}_{\rm out})\, M_\beta(\vec{k}_{\rm in})M^*_\beta(\vec{k}_{\rm out})\, \delta(\hbar\omega - \epsilon_\alpha + \epsilon_\beta)} - R_0(\hbar\omega) \quad (1)$$

where the uncorrelated part R_0 is proportional to the self-convolution of the optical density, $D(\hbar\omega) = \Omega^{-1}\overline{\sum_\alpha M_\alpha^2\, \delta(\hbar\omega - \epsilon_\alpha)}$. Fourier transformed into the time domain, a faint oscillation in the secondary emission signal can be traced back to quantum mechanical level repulsion in R_c, which in turn reflects characteristics of the underlying disorder potential.

A particularly interesting case is the decay of polarization, often interpreted as apparent loss of spin coherence. Recent experiments can be described quantitatively in a model involving interference of energy pairs split by the exchange interaction [3]. The splitting distribution is obtained for quantum wells with short-range interface roughness.

Resonant light emission in the back-scattering direction has not been studied experimentally in semiconductor quantum structures up to now. We predict an enhancement for disordered samples, which is analogous to the weak localization known from classical waves and quantum transport [4]. In the present context, it can be traced back to correlations between the optical matrix elements entering Eq. (1).

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"Coherence, luminescence, excitons - and all that ...."

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This talk provides a tutorial overview of microscopic aspects of semiconductor-light interaction involving coherent excitation, conversion of polarization to population, formation of excitons, as well as incoherent luminescence. Optical dephasing, i.e. the temporal decay of the macroscopic optical polarization is attributed to the destructive interference of its microscopic constituents due to various interaction effects, such as static disorder, carrier-carrier and carrier-phonon scattering etc. Conversion of polarization into electron-hole-pair and/or excitonic populations is discussed as well as the formation of excitons within an incoherent electron-hole plasma. Exciton ionization at elevated densities, i.e. the "excitonic Mott Transition" is revisited, emphasizing the subtle but important differences between excitonic signatures in optical spectra and incoherent excitonic populations.

Early stages of secondary emission in quantum wells

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In this talk, I will try to review the different experimental contributions to the study of secondary emission due to excitons in quantum wells at very early times. Two different regimes will specifically be addressed, resonant or non-resonant excitation.

In the first one, where the excitation is resonant with the excitons, and I will discuss the possible contribution of effects such as Rayleigh scattering[1], level repulsion[2], radiative coupling[3]... I will try to make a distinction between the polarization created by the laser in the sample and the population of excitons which appear after dephasing has occurred. The different possible experiments will be reviewed and discussed critically [4-7].

In the second case, where non-resonant excitation is used I will recall the experimental results (see for example [8,9], which all demonstrate that the luminescence is centered at the exciton energy at all times. I will discuss the possibility that this emission is due to a real population of excitons or rather to the transition between free pairs as suggested by [10] as well as different possibilities to measure how the formation of exciton proceeds [11,12].

This work has been performed by G. Hayes, S. Haacke, JD Ganière, JL. Staehli, M. Saba, C. Ciuti, C. Piermarocchi, V. Savona

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Microscopic Theory of Semiconductor Luminescence and Terahertz Absorption

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A fully microscopic theory for a semiconductor system of interacting electrons, holes, photons, and phonons is presented.[1,2] In this description, photon-carrier entanglement, phonons, free carriers, and excitons are described on the same level. This allows a consistent description of exciton formation, photoluminescence, terahertz (THz) absorption, intraband correlation effects [3,4], and other quantum optical effects. The resulting coupling of carrier correlation dynamics to *semiconductor Bloch and luminescence equations* [1,2] is discussed and evaluated for a variety of experimentally relevant situations.

Here, we concentrate on an incoherent situation where the system initially contains only electron-hole plasma. The following phonon-assisted exciton formation is investigated using different lattice temperatures and carrier densities; this analysis resolves the situations with clear atom-like bound excitons. When these exciton populations are present, their effect on photoluminescence is determined and a detailed comparison of exciton population and plasma contributions [5] is made. In the context of THz-absorption, an exact analogy between carrier correlations and optical Bloch equations is derived. As a result, the exciton number can be determined in the atomic sense for any excitation level. This analog allows us to identify the differences between semiconductor and atomic optics. We observe that semiconductor photoluminescence always includes a plasma component whereas THz-absorption depends on the correlated exciton populations directly.

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Structural and electronic studies of InAs quantum dots embedded in GaAs by scanning tunneling microscopy

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Abstract

Cross-sectional tunneling microscopy (XSTM) is a powerful tool to study the physical and chemical properties of III-V semiconductor structures on the atomic scale. Cross-sectional imaging is performed on (110) surfaces prepared by *in situ* cleavage. It has been used to investigate, for example, the interface roughness and the alloy fluctuations of superlattices and, more recently, of embedded quantum dots. As the tunneling current depends on the electronic properties of the semiconductor, the STM can also probe the electronic properties of such structures. This talk will detail STM results obtained on InAs quantum dots embedded in GaAs layers. Since the strain in InAs quantum dots leads to a displacement of the cleavage surface and since the sensitivity of the spectroscopic measurements depends on the distance between the probe and the surface, we will first discuss the contrast mechanism of the topographic STM images in order to correctly interpret the spectroscopic measurements. We will then investigate the electronic structure of individual quantum dots and show that the amplitude of the electron wave functions can be resolved for the ground and first excited-state at room temperature. As their is a need to reduce the confinement in such a dot, for fabrication of lasers operating at a wavelength of 1.3 μm, we will finally present recent investigations on doubly stacked layers of quantum dots.

Single and coupled quantum dot spectroscopy

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Semiconductor quantum dots have shown recently a remarkable potential for applications in lasers, amplifiers etc. In these systems the spectroscopic signatures of individual dots are usually hidden by the inhomogeneous broadening of the dot ensembles. By using mesa structures fabricated from self assembled dot layers individual dots become available for detailed spectroscopic studies. When the size of the mesa becomes comparable to the inverse dot density a mesa will contain only a few dots. By using conventional far field spectroscopy these dots can be probed. Due to the location of a dot in a specific mesa structure comparative studies in different experimental set-ups providing e.g. high spatial resolution, time resolved spectroscopy or magnetic fields are possible on the same dot.

The talk presents results on excitons in single dot structures as well as of excitons in single dot molecules. Single dots have been studied by luminescence and excitation spectroscopy. For example, the excitation spectra for dots with two and three confined levels show clear differences. In dots with three confined levels the p shell transitions show a splitting which is absent if the dot contains only two shells. The p splitting is associated to mixing of excitonic configurations of the three level dots. Dot molecules show a clear splitting of the ground state of up to 20 meV when the barrier layer between the dot layer is reduced to a few nanometers. In magnetic fields we observe different splitting patterns for various dot molecules which are most likely related to variations in shape and position between the dots forming the pair. By placing the dots in externally controllable electric fields the emission energy of the dots is modified. The shift of the emission energy allows to determine e.g. the dipole moment of the exciton in the dot.

Fabrication and Optical Properties of Quantum Dots: GaN-Based and InAs Quantum Dots

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We discuss our recent progress in fabrication and physics of quantum dots. Near-field spectroscopy of InAs quantum dots (QDs) showed existence of 2D-like continuum states and the number of sharp lines, between a large zero-absorption region and the 2D wetting layer. Near-field coherent excitation spectroscopy inditaed possibility of quantum mechanical control of the carrier wavefunction in the QDs. We also discuss InGaN self-assembled QDs on a GaN layer without any surfactants, using atmospheric-pressure MOCVD. A laser structure with the stacked InGaN QDs embedded in the active layer was fabricated and room temperature operation of blue InGaN QD lasers was achieved under optical excitation.

The concept of the three-dimensional quantum confinement of carriers in semiconductor quantum dots (QD) was proposed by Arakawa and Sakaki in 1982 [1], predicting the use of QDs in semiconductor lasers leads to significant improvements of the threshold current characteristics. After this prediction, various lasing characteristics, such as reduced threshold current density, reduced total threshold current, enhanced differential gain, and high spectral purity/no-chirpingwere theoretically discussed [2-6]. In the 1980's, however, the only way to demonstrate the QD effects in semiconductor lasers was to place quantum well lasers in high magnetic fields[6].

With the remarkable progress in self-assembling growth technologies in the 1990's [7-9], QD laser diodes were demonstrated by several groups[10-12]. The successful achievements of low threshold current due to the small volume effect and 1.3μm light emission convince us that the QD lasers will be in a commercial market in 3-5 years, although inhomogeneous broadening due to size fluctuations crucially affects the advantage expected theoretically, It is also important for QD lasers to extend their material from InAs to other semiconductors, particularly GaN-based lasers. In this paper, we discuss our recent progress in fabrication and physics of quantum dots, including single dot near-field spectroscopy of InAs quantum dots (QDs) and GaN-based QD for optoelectronics applications.

Comparison of near-field and far-field photoluminescence excitation (PLE) spectra gives new insight into the carrier relaxation process in InGaAs/GaAs self-assembled quantum dots[13]. The near-field PLE spectra of single QDs clearly show 2D-like continuum states and a number of sharp lines, between a large zero-absorption region due to the quasi-0D density of states and the 2D wetting layer absorption edge. The results reveal an efficient intradot relaxation mechanism, proceeding as follows: The carriers can relax easily within continuum states, and make transitions to the excitonic ground state by resonant emission of localized phonons.

Using the near-field optical microscopy, we have performed coherent excitation spectroscopy of self-assembled InAs QDs[14]. A pair of coherent pulses with a time delay between them allows measurement of the temporal coherence of the carrier wave function in single quantum dots. The observed decoherence time is about 15 ps and is well explained by resonant Raman scattering of phonons. Furthermore, quantum beats originating from the superposition of two closely

spaced coherent states have been observed. This opens up possibilities of quantum mechanical control of the carrier wave function in QDs.

The impact of the use of QDs on GaN-based semiconductor lasers strongly motivates us to making effort for fabricating the GaN-based QDs[15]. We have investigated InGaN self-assembled QDs on a GaN layer without any surfactants, using atmospheric-pressure MOCVD[16]. The average diameter was as small as 8.4nm and a strong light emission was observed at room temperature. The size of ~10nm is small enough to populate most of carries at the ground state[17]. We also established growth technologies of stacked QD structures in order to increase the density of InGaN QDs. A laser structure with the stacked InGaN QDs embedded in the active layer was fabricated and room temperature operation of blue InGaN QD lasers was achieved under optical excitation[18]. Carrier confinement in QDs was investigated using near-field μ-photoluminescence measurement: A very sharp spectral line emitted from excitons in individual InGaN QDs was observed[19]. We also investigated the selective growth of InGaN (GaN) QDs on GaN(AlGaN) hexagonal pyramids. Micro-photoluminescence intensity images with a spatial resolution of a few hundred nanometers show that the emission was only from the top of the hexagonal pyramids[20]. Finally, we also mention enhancement of spontaneous emission in InGaN blue light emittingVCSELs are demosntarated[21].

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A Quantum Dot Single-Photon Emitter

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A single photon source, which is able to generate photons on demand, has been a major challenge for many years. Such a source allows the ultimate quantum control to the photon generation process, i.e. single photons can be generated within short time intervals and a deterministic dwell time between successive photon generation events. This makes it possible to encode information on a single photon level. Such a source is of interest for future applications in quantum computing and quantum cryptography.

Our samples were grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The microdisks consist of a 5 μm diameter disk and a pedestal area. The self-assembled InAs QDs were grown in the center of the 200 nm disk region. The QD density of the sample was $<10^8$ cm^{-2}. The experimental setup combines a low-temperature diffraction-limited scanning optical microscope for spatially resolved photoluminescence (PL) spectroscopy and a Hanbury Brown and Twiss setup for photon correlation measurements. The system provides spectral resolution of 70 μeV, spatial resolution of 1.7 μm, and temporal resolution of 420 ps. The microdisks are mounted in a He gas flow cryostat. Optical pumping is performed with a mode-locked femtosecond (~ 250 fs, 82 MHz) Ti:sapphire laser, operating at 750 nm and generating electron-hole pairs in the GaAs layers.

We demonstrate heralded single photon emission from a self-assembled InAs quantum dot (QD). Pulsed optical excitation together with Coulomb renormalization effects allows for the realization of regular single photon emission at the excitonic transition (1X) with nearly 100 % efficiency. By temperature tuning, we are able to shift the 1X transition into resonance with a whispering gallery mode of a microdisk (Q ~ 6500) and achieve turnstile operation of the coupled QD-cavity system. On resonance, the Purcell effect causes a reduction of the 1X transition lifetime leading to a reduced time jitter of the photon emission event and ensuring that photons are primarily emitted into a cavity mode.

Periodic Structures and Efficient Nanocavities for Controlling Spontaneous Emission

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It has recently become possible to design and fabricate very small cavities in which the emission behavior of light can be modified. For example, the spontaneous emission rate can be increased within LED structures by defining a small low-Q cavity with metal mirrors. Conversely, the spontaneous emission coupling factor can be increased in nanocavity laser structures by including the light emitters into a high Q photonic crystal cavity. Here we compare the design, fabrication, and measurement results of such structures, and describe potential applications in microfluidic analysis chips.

VCSEL Pumped Photonic Crystal Lasers

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We report results from our work on the modeling, fabrication, and characterization of VCSEL pumped photonic crystal lasers. The lasers are optically pumped at room temperature under pulsed conditions. The optical pumping source is a VCSEL emitting near 850 nm.

The photonic crystal laser cavity is based on a two-dimensional photonic crystal etched into InGaAsP layers containing InGaAsP quantum wells for optical gain. The two-dimensional photonic crystals were defined with e-beam lithography. The patterning of the semiconductor was accomplished with an ECR etch at room temperature using CH_4/H_2. The laser cavity is formed in an undercut membrane with the photonic crystal providing in-plane optical confinement. The membrane is formed by chemically undercutting the InGaAsP layers with HCl. We will also report on our efforts to obtain room temperature CW operation from single defect structures that have been wafer-bonded to sapphire.

Modeling of the electromagnetic fields in these cavities will also be discussed. Results from finite-difference time-domain calculations as well as finite-element calculations will be included. The results will include modeling of the electromagnetic fields, cavity quality factors, far-fields, and the temperature distribution inside of the cavities. These calculations will be compared to our experimental results. We will also discuss our work on modeling the devices that have been wafer-bonded to sapphire. Here the sapphire complicates the electromagnetic design. The sapphire breaks the symmetry of the cladding layers and increases the radiation losses of the cavity. We will discuss strategies for obtaining high Q cavities in this asymmetric cladding geometry.

Progress towards photonic crystal integrated optics

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Photonic crystals provide a fascinating platform for a new generation of integrated optical devices and components. Circuits of similar integration density as hitherto only known from electronic VLSI can be envisaged, finally bringing the dream of true photonic integration to fruition. This development is very timely, as the exponentially increasing bandwidth requirement of the internet generation is pushing optical communications ever closer to the end user. Fibre optics has advanced from the provision of long-haul data transport into the metro and now even into some local area networks. The more complex the network, the more nodes are needed, which requires high-functionality photonic circuits. Photonic crystals may provide this functionality, and ultimately reduce a telephone exchange to the size of a thumbnail.

Recent progress in the field pushes this vision ever closer to reality. Waveguides in 2D photonic crystals with propagation losses in the 5-10 dB/mm regime have now been realised, dispersion properties are better understood, and the large modal mismatch between fibres and these microphotonics elements is being addressed. Wavelength-selective elements based on cavities and lattices have also been reported, thereby enabling WDM functionality.

Overall, there is now clearer evidence that photonic crystals may indeed provide a useful platform for the next generation of photonic circuits. This exciting progress, as well as some of the remaining problems, such as polarisation dependence and active functionality, will be discussed.

Tuning Photonic Crystals

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Photonic crystals are dielectric materials with a spatial periodicity in the dielectric constant. Just as semiconductor materials have fostered the first phase of the communications revolution by controlling the flow of electrons, photonic crystals may help foster the 2nd phase of this revolution by controlling and molding the flow of light. One of the characteristic features of a photonic crystal is the existence of a stop gap, a frequency region over which light cannot propagate for certain directions. If light is inhibited from propagating in all possible directions over a certain frequency range one refers to the interval as a photonic band gap. Stop gaps and band gaps can add novel functionality to photonic devices through, *e.g.* control of spontaneous emission or transmission characteristics. The ability to tune a photonic gap can open up new vistas for photonic crystals in fundamental and applied science. In this talks I will discuss our work on the use of liquid crystals or free carrier injection to tune photonic gaps in 2-D photonic crystals made from silicon.

"Slow, highly nonlinear propagation in waveguide-disk-resonator structures"

Richart Slusher
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Experiments are in progress to explore "dumb" slow light propagation in waveguides coupled to microdisk resonators. These structures are being fabricated using chalcogenide glasses with nonlinear coefficients nearly 500 times silica glass. The excellent figures of merit in these materials and structures is promising for a wide variety of optical communication applications.

Controlling the interaction between light and gold nanoparticle arrays

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Abstract: The interaction of light with gold nanoparticle plasmons can be controlled by geometrical arrangement of nanoparticles on a waveguide. Coupling of the particle-plasmon to the incident light and the waveguide modes results in selective suppression of extinction.

Tailoring the light-matter interaction via proper design of periodic nanostructures is one of the most fascinating and active topics of current solid state physics. The rapidly growing research activities in this field include in particular the development of photonic crystals. We show that a rectangular 2-dim array of gold nanoparticles on top of a suitable dielectric waveguide leads to a collective interaction of the gold nanoparticles with light, resulting in selective suppression of extinction [1].

The optical extinction of a single gold nanoparticle is governed in the the visible by the particle-plasmon resonance, which is well described by the Mie theory. Previous work [2-3] has shown that the optical properties of the particle-plasmon in 2-dim arrays can be modified by either regular arrangement of gold dots or by coupling of the particle-plasmon to a surface mode.

We performed extinction measurements for normal incidence of a white light beam on different gold nanoparticle arrays fabricated by electron beam lithography on a 140 nm thick ITO film. The nanoparticles had a diameter of around 100 nm and a height of about 20 nm. The period in one direction was changed from 350 nm to 475 nm in steps of 25 nm, while the other period was kept at 300 nm. Upon changing the period, two dips with suppressed extinction appear in the absorption spectra, shifting towards the lower energies. The separation of the dips is 50 meV.

Excitation of the particle-plasmon leads to absorption and scattering of the incident light and is therefore responsible for the broad extinction spectrum. For our experimental parameters, the ITO film acts as a waveguide [4]. Du to the regular arrangement of the particles, a part of the incoming light can be coupled into the waveguide for certain photon energies. For normal incidence, two energetically degenerate waveguide modes are expected for an unperturned waveguide.

If the waveguide is excited, the total electric field acting on the nanoparticle consists of two components: the incident electromagnetic field and the filed of the waveguide mode. Since the polarizations created by both fields are 180 degrees out of phase [5], we obtain destructive interference at the metal dot positions which results in reduced coupling between light and the particle-plasmon. The regular array of gold nanoparticles removes the energetic degeneracy, so that even for normal incidence, two spectrally separated dips appear in the extinction spectrum. Since the spectral width of the two waveguide modes is considerably narrower than the particle plasmon resonance, the photonic interaction mediated by the waveguide is only supported for two narrow bands within the particle plasmon resonance. Tuning these bands by varying the periodicity of the dot array and thewaveguide thickness therefore allows complete control of the photon-particle-plasmon interaction. Changing the incidence angle maps the energy dispersion of our coupled modes. This implies a variety of interesting applications for optical ICs and telecommunication.

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Quantum Dots: Artificial Atoms and Quantum Computing

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The data shows that semiconductor quantum dots have optical properties very similar to simple atomic systems but are surprisingly robust against decoherence and have large dipole moments. By combining advances in nano-optical probing methodologies with the power of coherent nonlinear optical spectroscopy techniques, the measurements have enabled us to extend concepts of coherent optical control and wave function engineering to a single quantum dot exciton. Moreover, these dots have formed the basis for several proposals for quantum logic devices of interest to quantum computation. Our measurements have now provided the first observation of optically induced and detected quantum entanglement of the pseudo spins associated with two different excitons. Measurements of the associated Raman and biexciton induced coherence and the resultant decoherence will be presented.

Theory of ultrafast light manipulation of spin-excitons in nanodots for quantum computing

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We propose a quantum control of the exciton spin dynamics with due attention to exciton interaction and the dephasing effect of the environment. We give examples of possible applications to quantum information and computation and assess their feasibility by nu-merical simulation of complete sequences of quantum algorithms.

Experimental laser control of spin states of excitons has been demonstrated in ensembles of semiconductor quantum dots (QDs). In a single dot, ultrafast control of spin-excitons, and entanglement of the electron-hole complex have been reported. This work presents a step furthering a new perspective of proactive control of the spin-exciton dynamics in the quantum limit. We calculate the coherent nonlinear spectra as a function of pump intensity to find features which would indicate the possibility of coherent exciton control. Laser manipulation of spin-polarized optical excitations in a semiconductor nanodot is proposed to control the spin dynamics of two interacting excitons. Shaping of femto-second laser pulses keeps the quantum operation within the decoherence time. Computation of the fidelity of the operations is used to judge the quality of the design of quantum control.

To illustrates the issues raised above, we present the results of numerical simulations of prototype quantum computations. They consist in simulating the two exciton dynamics in a quantum dot which can accommodate several excitons as a sequence of operations to solve the Deutsch-Jozsa (DJ) problem and the quantum Fourier transform. Included in the simulations are the effects unintended dynamics and decoherence.

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Angular resolved emission of cavity-polariton under resonant excitation

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Since the first observation of cavity polaritons, there has been a number of controversial reports in non-linear experiments of laser-like dynamics of the photoluminescence of cavity polaritons and its interpretation in term of stimulated boson amplification or Bose Einstein Condensation. On the other hand little investigation has been reported on coherent scattering of cavity -polaritons in the linear régime.

We will discuss both aspects using far-field and near-field analysis of the CW photoluminescence. Energy and k-conservation lead to elastic scattering occurring on a ring in the far-field image. Rayleigh scattering can be distinguished from resonant hot luminescence by its polarization and the presence of speckle structures. We will show that elastic scattering of light in a situation of strong light coupling in a semiconductor system yields detailed information on the eigenstates of the 2D cavity-polariton system, in addition to providing a prototype of a 2D system to study light scattering. Moreover the strong coupling between the excitonic oscillator and the cavity mode enables the simultaneous observation of both i) universal properties of disordered systems such as coherent backscattering over a large angular width, and ii) scattering anisotropy due to the microscopic nature of the scatterer. Such experiments provide a bridge between light scattering experiments in disordered systems and the physics of strongly-coupled microcavities.

Under increasing excitation, a transition to a spatially patterned, highly-emissive state is observed. This is attributed to a combination of nonlinear cavity-polariton relaxation along with the nonlinear response of the cavity. Polariton-polariton scattering, which conserves both energy and momentum, can be viewed as parametric amplification (or non-degenerate four wave mixing) where 2 cavity-polaritons scatter simultaneously from k=k' to k=0 and k=2*k'. In our experiments, the thermal PL acts as an idler (probe) which seeds the parametric process. After a certain pump intensity there is sufficient power to provide gain at k=0. Many of the features observed in our experiments such as a blue shift of the non-linear emission with respect to the cavity mode by a quantity of the order of the cavity-polariton homogeneous linewidth are also predicted in this model. In addition quantum noise measurement shows a phase dependence of the amplification which is typical of coherent multiwave mixing process.

"Microcavity Polariton Traps: What do you get if you cross light and matter?"

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Abstract not available

PARAMETRIC EMISSION OF MICROCAVITY POLARITONS

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The nonlinear optics of semiconductor microcavities in the strong exciton-photon coupling regime is a rapidly developing domain. The exciton-polaritons have been found to dominate the optical response under resonant excitation for particle densities well below the critical saturation value due to the Pauli blocking. In particular, Savvidis *et al.* [1] have reported the first observation of giant polariton amplification through angle-resolved pump-probe experiments. Polaritons can be pumped resonantly at a specific wave-vector and their relaxation can be stimulated coherently by a weak probe beam which results to be amplified. The scattering process responsible for the signal gain is the conversion of a pair of pump polaritons into a signal-idler pair, where the idler polariton allows the energy-momentum conservation. This sort of polariton parametric amplification has been well explained within a model of interacting bosons for the polariton system [2]. The polariton picture provides a unified description for the temporal, spectral, angular and intensity-dependent features. More recently, we have extended the treatment to the regime of parametric luminescence below threshold which is the dominant emission when no probe is applied [3]. The parametric correlation between polariton pairs produces novel collective excitations [4] with anomalous energy dispersion which can give rise to vanishing or even negative in-plane group velocities (light-induced negative mass). The build-up of the polariton population is shown to be driven by the parametric pair correlation which is itself stimulated by the polariton populations. Above the stimulation threshold, the transfer of pumped polaritons into the signal and idler modes is macroscopic. In the pulsed experiments, the signal and idler fields are so intense that additional channels (e.g. signal-signal scattering) are opened. To account for these additional effects, we have generalized the polariton parametric amplifier equations [2] to the multiple scattering regime, explaining several puzzling features observed in ultrafast pump-probe experiments [5], such as strongly nonlinear emission at the pump back-scattering angle. The emission shows a rich spectral structure with resonances which can be dramatically off the original polariton branch. We explain the relationship between these multiple resonances and the macroscopic coherence at the signal and idler modes. Finally, the anomalous multi-branch angular dispersion provides a good fit to the angle-resolved luminescence data [5].

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Nonlinear Magneto-optic Quantum Micro-cavities

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We present theoretical and experimental studies of the nonlinear behavior in a magneto-optic quantum micro-cavity in the strong coupling regime. The experimental studies were performed on a semi-magnetic semiconductor quantum micro-cavity using nonlinear Faraday rotation and reflectivity techniques. The nonlinear behavior was traced to photo-induced modifications of the exciton-polariton features. Extensions are presented.

The study of exciton-polariton modes received a renewed attention in the recent years with the use of quantum micro-cavities where the material (exciton) and electromagnetic (photon) components can be independently and artificially modified through appropriate matching of micro-cavities and quantum well characteristics [1,2]. The exction-polariton can be modified by external electric and magnetic fields. Its features are also very sensitive to light induced changes and this allows in particular to assess the nonlinear regime, its dynamics and the effective exciton-cavity coupling.

We have performed a theoretical and experimental study [3,4] of the nonlinear behavior of a magneto-optic quantum cavity in the strong coupling regime and were able to delineate the main photo-induced mechanisms that are effective there. The effects are efficient by judicious enhancement of the magneto-optic coupling as can be achieved through the spin-exchange interaction in semi-magnetic semiconductors with moderate magnetic field intensities and the use of asymmetric micro-cavities.

In our experiments the micro-cavity consisted of a single quantum well Cd_{1-x} Mn_xTe and the measurements were performed at 5K and with applied magnetic field intensity of 0.2T. A well controlled and characterized tunable coherent source delivering pulses of 10ps was used. Reflectivity and Faraday rotation spectra were measured.

At high laser intensities and with the laser frequency close to the exciton frequency large exciton densities are generated which influence the characteristics of the exction polariton mode. We have evidenced both saturation and many body interaction mediated shifts of the exciton transition which modify its oscillator strength and resonance frequency. In their turn these modifications influence the coupling between the exciton and the cavity modes through the concomitant reduction of the Rabi frequency and level shifts.

The Faraday rotation spectra were recorded for moderate laser fluences (typically up to 1-3 $\mu J/cm^2$) and magnetic field intensities (typically 0.2 T). The Faraday technique shows very high sensitivity with respect to frequency changes and different circular polarization states and was extensively used to map out the photo-induced changes.

The modifications were relatively mild in the case of large exciton and cavity frequency detuning (untuned micro-cavity). On the other hand the impact of the light intensity changes were striking when operating at zero detuning (equal exciton and cavity frequencies, tuned cavity). Actually the micro-cavity could be switched from the tuned to the untuned state by increasing the laser intensity by mere 1-3 $\mu J/cm^2$.

The measurements and the observed behavior were also accounted for in terms of a model incorporating the Rabi and Zeeman splittings of the exction transition of the quantum well inside the micro- cavity and also introducing the light modification of the material (exciton) component. Several extensions and cavity configurations were considered with particular attention on the non-linear magneto-optic Fabry Perot cavity [5] where polarization state controlled multistable operation can ocur.

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Exciton-polariton lasers and amplifiers

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Bosonic final state stimulation of microcavity exciton polaritons has been recently observed in the two distinct systems, parametric amplifier (nonlinear susceptance oscillator) and laser amplifier (negative conductance oscillator). In this talk, we will review the recent experiments of polariton amplifiers and lasers in GaAs and CdTe quantum well microcavities. Experimental evidences for stimulated exciton-exciton scattering and lasing and amplification based on the incoherent exciton reservoirs will be presented. Quantum statistical properties of emitted light and a new concept of stimulated tunneling for an electrical pump device will also be discussed.

Stimulated Scattering in Semiconductor Microcavities

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Recent work on non-resonant and resonant excitation of semiconductor microcavities carried out at Sheffield will be described. Where possible contrasts and parallels between the two cases will be drawn.

Under conditions of non-resonant excitation clear evidence for a relaxation bottleneck in the polariton population is found. For a wide variety of negative detunings, at low excitation powers, a clear peak in the polariton population away from the centre of the Brillouin zone is observed in angle resolved photoluminescence experiments. With increasing power the bottleneck is suppressed due to the increasing importance of polariton-polariton pair scattering with increasing photocreated exciton density. No clear evidence for polariton stimulated scattering is found up to a density of $\sim 10^{10} cm^2$ where the strong coupling limit collapses due to the high population of high k excitons and free carriers created which give rise to screening.

The situation is found to be very different for the case of resonant excitation of the lower polariton branch at wavevector k_{las}. In this case, above a very clear threshold in laser power, very strong emission at k=0 and at $2k_{las}$ is observed in a parametric process which conserves energy and momentum, whilst at the same time the system remains in the strong coupling limit. The threshold for stimulation is observed at state occupancies close to unity, consistent with a final state bosonic explanation for the stimulation process. Most surprisingly such parametric scattering and stimulation are found for a wide variety of excitation angles from 5 to 20 degrees (not only at the 'magic angle' at the point of inflection of the dispersion curve) with very similar thresholds being seen. This result shows the generality of the stimulation phenomena observed, in part very likely because of renormalisation of the dispersion curves close to stimulation. The marked contrast between the resonant and non-resonant excitation cases is discussed in terms the effectiveness with which low k polaritons are created for the case of resonant excitation, whereas for non-resonant excitation a high density of high k excitons is created which gives rise to screening and loss of strong coupling, before the onset of polariton stimulation.

I would like to acknowledge the major contributions to this work of M S Skolnick, R Butté, R M Stevenson, M Emam-Ismael and J S Roberts at Sheffield, J J Baumberg and P G Savvidis at Southampton and D M Whittaker at Toshiba Cambridge

Spontaneous and stimulated polariton relaxation.

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The question of polariton relaxation stimulated by the final state population, related to the bosonic nature of these quasi-particles, has been a highly debated topic these two last years. A stimulation of the polariton relaxation should lead to non linear behaviors for example in emission. However one has to be very careful before concluding about such a stimulated scattering since spontaneous polariton-polariton scattering or a standard laser emission in the weak coupling regime can also lead to a non-linear emission.

We will show that under non-resonant excitation, a quadratic non-linearity is observed in emission and is related to the collapse of a relaxation bottleneck assisted by polariton-polariton interactions. Measurement of the occupation factors shows that this process is fully spontaneous [1]. Even in a sample with a large number of quantum wells and large Rabi splitting, the regime of stimulated scattering could not be observed under non resonant excitation before bleaching of the strong coupling regime.

However stimulated polariton relaxation can be observed with selective resonant excitation [2]. We will discuss time resolved measurements under oblique resonant excitation. In such a geometry, polaritons created at a given in-plane wave-vector k_{exc} can be scattered to k=0 through the following mechanism : 2/kexc> -> /k=0> + /2kexc>. We monitor the time evolution of the polariton emission for various k//. When increasing the excitation power, the polariton distribution in k-space is completely modified. A huge non-linearity is observed for states close to k// = 0, associated with a drastic change in the emission dynamics.

Finally we will describe pump-probe measurements [3] performed in several III-V and II-VI microcavities. Very efficient light amplification due to polariton-polariton parametric amplification could be observed up to 120 K in GaAlAs-based microcavities and up to 220 K in CdTe-based ones. Our results indicate that the critical parameter which determines the cut-off temperature is the exciton binding energy so that working with materials with a higher exciton energy (like ZnSe) could lead to room temperature operation [4].

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To be announced

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Abstract not available

Structural, optical and electrical spectroscopies of quantum dots at nanoscale

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A detailed assessment of the quantum dot properties is a crucial step for the implementation of GaAs-compatible quantum dot lasers with improved perfomances (low threshold, high critical temperature, no Peltier Cooler). To this aim we have developed a class of nanoscale methods for the structural, optical and electrical study of single quantum dots. The samples are InGaAs quantum dots grown by MOCVD, embedded in wider gap InGaAs or GaAs waveguides. First of all one has to measure the actual composition of the dot, to such an extent that the emission wavelength is controlled with high precision. Single dot compositional assessment has been performed by using spatially resolved Electron Energy Loss spectroscopy with 2 A resolution, emploing a FEG-STEM. Cross sectional scans were perfomred both on the wetting layer and on the dots, showing the depletion of In in the wetting layer underneath the dot, and the enrichment of In at the apex of the dot. The In profile across the dot cross section was found to vary between 33% in the wetting layer, about 50% at the basis of the dot and up to 62% at the apex. Such values should be compared to the expected homogeneous composition of 50% In. Due to such internal interdiffusion, the electron-hole wavefunctions turn out to be separated in the dot, thus generating an internal dipole which causes considerable shift of the dot ground level. A full theoretical modeling of these data shows that the emission wavelength of the dots shifts by about 30 meV with respect to the design wavelength. Once the composition and shape of the dots are determined precisely (the latter by high-resolution TEM), we have investigated the single dot spectra by using low-temperature SNOM and low-temperature scanning tunneling luminescence. In the former case the spatial resolution amounts to about 100 nm, whereas the STL provides a resolution of about 20 nm. Besides the usual occurrence of band filling spectra involving 1s, 1p, and 1d excitons and related many-body states, we have observed a dominant diffusion of carriers in the as grown samples. This normally prevents the observation of lifetime limited ultranarrow single dot lines. This problem has been solved by fabricating by electron beam lithography ultrasmall mesa (about 80^{80} nm^2) containing just a single dot. In this case it has been possible to observe the sharp lines and all the Coulomb correlated states connected to biexcitons and charged excitons.

Finally, we have developed a current-voltage STM spectroscopy to probe the charge density and the wavefunction contour plot in a single dot. Transconductance STM experiments show the charge density of the 1s and 1p states in doped dots. These are directly correlated to the calculated wavefunction contour plot, showing the hole wavefunction spread at the bottom of the dot (extension 18 nm) and the electron wavefunction at the apex of the dot (extension 12 nm) due to the dipole-induced separation.

Quantum dot lasers obtained after such a long optimization procedure will be shown at the end of the talk.

Exciton Relaxation in Quantum Dots and the Application to Lasers and Microcavity Light Emitters

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Carrier dynamics in self-organized III-V quantum dots (QDs) has gained the interest of many researchers. Because the 3-dimensional confinement leads to discrete energy levels, the QD dynamic response is strongly influenced by its 0-dimensional energy levels. Recently we showed that excitons confined in different types of QD heterostructures can have strikingly different relaxation characteristics. Excitons captured by large InGaAs QDs with closely spaced energy levels exhibit relaxation times from the wetting layer to the QD ground state of 1 psec or less, while excitons confined in smaller InAs QDs have relaxation times of ~7 psec or longer. It is generally believed that the electron-hole interaction can speed the exciton relaxation rate, and other carrier-carrier interactions may also be important. The 0–dimensional energy levels also establish the temperature dependence of the QD light emission.

In this talk we discuss recent experiments performed to characterize the energy relaxation of charge carriers in self-organized QDs and, time permitting, discuss their application to lasers and microcavity light emitters. We find several interesting phenomena that directly ties to the exciton number and carrier number in the QD. By controlling the QD growth conditions we can control their size, and femtosecond spectroscopy is used to study the detailed relaxation processes of single excitons and multiple excitons in QD ensembles. The measurements are also sensitive to the fact that the light comes from an ensemble, since parts of the optical signal inevitably arises from QDs with different numbers of excitons.

In general we find that the exciton relaxation is a cascade process in multilevel QDs. That is, the relaxation appears to proceed by a series of relaxations through each QD energy level. For small exciton numbers the QD relaxation time appears to be insensitive to the exciton number. Time resolved ground state luminescence and first excited state luminescence are used to characterize the approximate time an exciton requires to relax from one energy level to the next. Carrier-carrier interactions and transition rules are also studied using modulation doped QDs. A general trend is that when the carrier density in the QD is significantly increased both the interlevel relaxation and luminescence emission rates are increases substantially. Transition rules between different energy levels are also studied to explore allowed radiative transitions between different electron and hole states.

Ultrafast gain dynamics and dephasing times in quantum-dot amplifiers from room to cryogenic temperature

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Time-resolved four-wave mixing and differential transmission spectroscopy are measured from 300K to 7K in an electrically-pumped InGaAs quantum dot (QD) optical amplifier. The investigated sample is a PIN structure grown by MOCVD containing in the active region three stacked layer of self-organized $In_{0.7}Ga_{0.3}As$ QDs separated by 35nm-thick GaAs spacers. Two AlGaAs cladding layers and a ridge structure of 5μm width and 500μm length provide optical waveguiding. The end facets are tilted allowing for electrical injection and suppression of multiple reflections and lasing. Amplified spontaneous emission and photoluminescence spectra show a dot ground-state transition of 60meV inhomogeneous broadening, separated by 65meV from the first optically-active excited-state transition and by ~210meV from the wetting layer, indicating the strong quantum confinement of the investigated dots. QD lasers fabricated from the same structure showed ground-state lasing at room temperature with low threshold current densities (~100A/cm^2). The experiment is performed using an optical parametric oscillator providing Fourier-limited ~150fs pulses at 76MHz repetition rate, with a wavelength tunable to the center of the dot ground-state transition ranging from 1170nm at 300K to 1070nm at 7K. At this wavelength position we estimate a negligible contribution (2%) of the excited-states to the optical density of states. Two pulses are coupled into the TE waveguide mode with a relative delay time and the signal is detected using an heterodyne technique similar to the one discussed in our previous work[1], but modified for the high-repetition rate with improved signal-to-noise ratio. The implementation of this technique at cryogenic temperature is made possible by holding the sample in a specially designed cryostat allowing for light coupling in and out of the waveguide with high numerical aperture.

Two main results from the experiment will be emphasized. 1) In presence of electrical injection, lowering the temperature decreases the thermal spread of carriers into higher excited states in favor of a more efficient filling of the ground state which also results in a reduced transparency current (from 300K to 150K) and in an increased differential gain. The impact of the carrier thermalization to the gain recovery dynamics as measured in differential transmission will be discussed. 2) Without electrical injection, the dephasing time of the dot ground-state transition is measured with four-wave mixing and its temperature dependence from 300K to 7K will be presented. The impact of these results in the understanding of the line broadening in III-V InGaAs quantum dots as compared to single-dot spectroscopy will be discussed.

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Cavity QED of quantum dots with dielectric microspheres

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A mesoscopic structure where single quantum dots (QDs) couple strongly to a single mode of electromagnetic field provides a model system for controlling fundamental optical interactions in QDs. In the extreme limit that the dipole-coupling rate between a QD and a resonant cavity mode exceeds relevant decoherence rates, spontaneous emission from the QD, which is usually viewed as an irreversible decay process, becomes reversible. To realize such systems, we have developed a composite optical microcavity by coupling colloidal QDs such as core/shell CdSe/ZnS nanocrystals to whispering gallery modes (WGMs) in a dielectric microsphere.

By embedding CdSe/ZnS nanocrystals in a polystyrene sphere, we have demonstrated enhanced spontaneous emission when the nanocrystals are resonant with a WGM. The manifestation of the enhanced spontaneous emission depends on temperature and especially on nanocrystal sizes, providing a unique probe to the underlying radiative dynamics.

By attaching nanocrystals to the surface of a fused silica microsphere, we have also demonstrated a QD-microcavity system with a Q-factor of order 10^8, four orders of magnitude greater than that of monolithic semiconductor microcavities. This extremely high-Q QD-microcavity system puts us in a regime where effects of a single QD on dynamics of the cavity become important. The composite nanocrystal-microsphere system should open up a new avenue to a variety of physical phenomena such as single-QD lasers and QD-based quantum information processing.

Theory of excitonic Rabi flopping, quantum interference and dephasing in single quantum dots

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Semiconductor quantum dots are attracting much interest as a candidate to implement the quantum information processing and the quantum computation. We study the excitonic Rabi flopping in a single semiconductor quantum dot to examine the possibility of the quantum state manipulation. One of the most striking manifestation of the quantum coherence is the Rabi flopping. The observation of the excitonic Rabi splitting in an InGaAs quantum dot was reported recently [1]. Under the strong excitation of an excited exciton state, the luminescence from the exciton ground state shows a doublet splitting. This splitting can be interpreted in the dressed exciton picture. In this case, the coherent superposition is driven by the excitation light between the excited exciton state and the ground state of the system. It is very interesting to probe this coherent superposition in the time domain using a phase-locked pulse pair. We consider an experiment in which the time-integrated luminescence intensity from the exciton ground state is monitored as a function of the time difference between two phase-locked pulses. The theory predicts an oscillatory behavior in the correlation trace which demonstrates the Rabi flopping. This oscillatory behavior has been observed recently [2]. In a quantum dot two-exciton states are easily excited under strong excitation. The quantum interference occurs between paths through only the exciton states and paths through the biexciton states, depending on the polarization directions of the pulses. When the time-integrated luminescence intensity from the exciton ground state is monitored as a function of the time difference between two phase-locked pulses, the correlation traces show various features of the quantum interference revealing the role of the two-exciton states. We discuss the dephasing of excitonic states. A general formulation was established to calculate the dephasing rate of generally non-radiative coherence between a pair of states [3], although the mechanism is restricted to the virtual emission and absorption of acoustic phonons. Based on this formulation, the dephasing time of dark excitons was calculated and was found to be as long as μs at low temperatures. This result is very encouraging for such an application as proposed in ref. [4].

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Coherent Manipulation of the Cold Biexcitons in CuCl

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Search for systems with long lived quantum coherence is driven by the growing interest to the quantum information technology, which practical implementation has become the most attracting target. Recent advances in atom cooling and trapping illuminate the advantage of optical technique for preparation of macroscopic quantum coherence. Although the main attention here has been focused on the BEC of atoms, it is well known that BEC has also a long history in semiconductors, in which macroscopic coherence is possible in a dense gas of the bosonic quasi-paritcles, i. e. in ensemble of excitons or biexcitons with ultra-narrow momentum spread and low temperature. [1]

We have recently demonstrated the creation and manipulation of long-lived coherent biexcitonic ensemble with high quantum degeneracy, full controllability of phase and amplitude, and easy optical accessibility. In this talk, we will present these results and discuss the future prospects regarding to (i) many body quantum physics including cross over from highly degenerate Bosonic to Fermionic ensemble [2], and (ii) creation of the efficient source for non-classical light for quantum information technology applications.

In order to create the biexcitons with a small momentum spread, we employ the two polariton fusion in CuCl under the strict resonant condition. In this process the high frequency component of the incident laser pulse couples with the low frequency component to fulfil the two-photon transition while satisfying energy and momentum conservation. This allows us to create long-living biexciton ensemble with an ultra-high phase space density and temperature of tens of micro-Kelvin. The coherence of the biexciton ensemble ensures a high visibility interference pattern from two biexcitonic waves, which are created by two well-separated optical pulses. The pattern fringe period corresponds to the biexciton frequency in CuCl. We would like to emphasize that in contrast with the conventional coherent control technique, in our experiment, optical polarization vanishes after passage of the pulse, while biexcitonic coherence survives making possible the phase coherent amplification.

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Reference

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Polar bear fiber optics, twenty years later:
Fuzzy Wuzzy wasn't photonic, was he?

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Abstract:
For over 20 years, dozens of newspaper and magazine articles, books and documentaries have peppered the public with the myth that polar bear hairs act as UV waveguides. How did this myth start? How has it come to be believed so fervently by so many? And what exactly are the specs of the world's first wireless ursine telecommunications link? Find out all this and more as we explore the origins of this scientific urban legend.

Local Field Effects in a Dense Atomic Vapor

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The Lorentz-local field results in a frequency shift of resonances in an optically dense material, known as the Lorentz-Lorenz shift. Although it was first predicted in the late 1800's, its was not observed until the 1990's, when several frequency domain measurements on dense atomic vapors succeeded in observing its characteristic density dependence in a dense atomic vapor [1]. The long interval between prediction and observation was due to the difficulty of working at high vapor densities and the corresponding extremely short absorption lengths.

Optical spectroscopic studies of semiconductors are typically performed using time domain techniques due to the extremely short relaxation times. Since semiconductors are optically dense, the local field needs to be considered. In transient-four-wave-mixing (TFWM), the local field results in a breaking of the time ordering requirements that would apply for a simple two level system, i.e. a signal can be produced for a "negative" delay [2]. However, such negative delay TFWM signals can be produced by several many-body effects, not just the local field. In addition, it is difficult or impossible to systematically vary the optical density in a semiconductor. Both of these strongly hinder a careful study of the contribution of local fields to the TFWM signal in semiconductors.

To address this, we have performed TFWM studies on a dense atomic vapor. At sufficiently high density and temperature, the dephasing times in a potassium vapor are only a few picoseconds, making TFWM studies with ultrafast pulses practical. We observe the signal for negative delay that is produced by the local field. The signal can be observed for over an order of magnitude variation in number density. Since the relevant parameters are relatively well known, a quantitative comparison with theory is possible, whereas in semiconductors it is not. This will provide insight into the coherent response of both atomic vapors and semiconductors.

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Coherent control of carriers, currents, and spin currents in semiconductors

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For excitation frequencies above the band gap of a semiconductor or insulator, qualitatively new nonlinear optical phenomena appear. Shift currents arise during excitation due to the difference in the centre of charge in valence and conduction bands. As well, macroscopic electrical currents and spin currents can actually be injected, involving average carrier velocities of hundreds of kilmetres per second. The latter effects involve electrons and holes acquiring momentum and angular momentum from the crystal lattice, and can be understood as arising from a quantum interference between the different pathways leading to absoprtion. Such quantum interference can lead to the coherent control of carrrier populations as well. These phenomena appear both in crystals that lack centre-of-inversion symmetry and in those that do not, but in qualitatively different ways. Typically the effects can be seen in bulk crystals at room temperature, but some should be enhanced in nanostructure geometries. Recent theoretical work has focused on understanding these phenomena in the context of nonlinear optics, making realistic predictions of the size of such phenomena, and exploring material systems in which they might be particularly interesting. Experimental work has focused on observing these phenomena in simple geometries, and in developing experimental protocols for their detailed study. Both theory and experiment will be reviewed.

Ultrafast coherent electron transport in GaAs/AlGaAs quantum cascade structures

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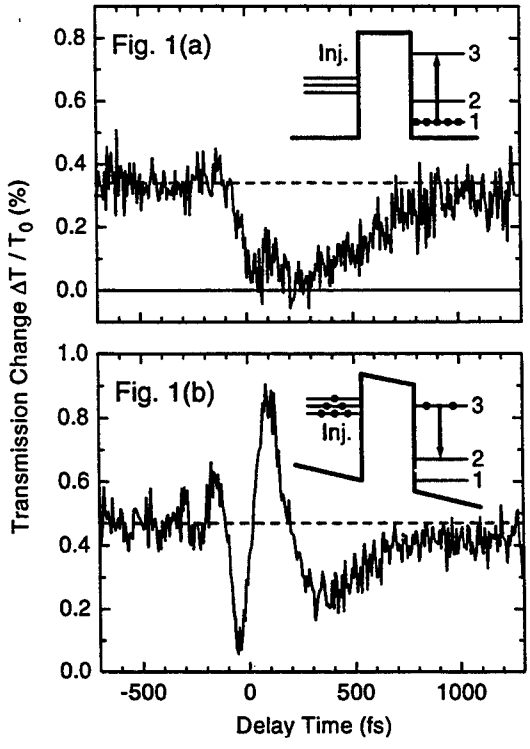
Although the design and production of quantum cascade lasers (QCL) [1,2] have reached a high degree of sophistication, direct experimental information on the microscopic mechanisms is still poor. The transport of electrons from the injector into the upper laser level plays a key role in such devices. Optimum design strategies try to enhance the injector–active-region coupling via resonant tunneling [3]. The underlying **coherent nature** of electron transport, however, is up to now not demonstrated experimentally. The interplay between electron wavepacket propagation and dissipative scattering processes determines the coherence degree of quantum transport [4]. Here, we present the first direct time-resolved study of the quantum transport from the injector into the active region. We have performed femtosecond pump-probe measurements on a GaAs/AlGaAs QCL structure using pump and probe pulses centered at a wavelength of 10 μm The probe pulses are spectrally resolved after interaction with the sample [5].

In Fig. 1, we show results for two detection wavelengths: (a) resonant to the 1-3 transition of the (unbiased) QCL at $\lambda_{det} = 9.2$ μm, and (b) at the maximum of the gain spectrum (3-2 transition) at $\lambda_{det} = 10$ μm. The measured transients represent the difference between a pump-probe curve with applied current (current density 7 kA/cm^2) and the pump-probe curve without current as a function of the time delay between pump and probe pulses. At $\lambda_{det} = 9.2$μm the applied current leads to a transmission increase before delay zero which is reduced during excitation and subsequently recovers within 1 ps. At this λ_{det}, we expect without bias an ultrafast bleaching due to the depopulation of level 1 and a recovery due to the repopulation of level 1. With bias we get zero pump-probe signal, since level 1 is unpopulated. Thus, the transient in Fig.1(a) represents the negative bleaching of level 1 for zero bias. Fig. 1(b) shows a transient at the gain maximum. The transmission increase before delay zero is due to current-induced gain [5]. Upon excitation it saturates and recovers within 800 fs. Superimposed to that incoherent contribution (exponential recovery) we find **pronounced oscillations** of the signal for delay times up to 400 fs. The oscillation points to coherent transport between the injector and level 3. In depleting the gain, the pump pulse induces a coherent superposition of level 3 and one of the injector levels.. This "hole" wavepacket propagates quickly across the barrier into the injector where carrier-carrier scattering leads to a strong damping of the quantum coherence.



First calculations of quantum transport in this QCL based on nonequilibrium Greens functions [4] are in excellent agreement with the experiment predicting. **oscillations of the coherent transport** between the injector and level 3 with frequencies close to the results of our experiment.

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Optically induced coherent transport phenomena in semiconductor nanostructures with disorder

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Traditionally coherent electronic transport phenomena in disordered solids, as e.g. Anderson localization, are studied in a scenario where the electronic system responds to an applied dc- or low-frequency electric field. In this talk it will be shown that, alternatively, ultra-fast optical experiments on disordered semiconductor nanostructures open up a new perspective for the investigation of coherent electronic transport in disordered systems, which allows to study the simultaneous influence of both, the interaction with disorder and the many-particle interaction, on transport. On the time scale of an optical pulse either an initial wave packet or an initial homogeneous current can be generated. In the course of time these initial states develop in a coherent way under the influence of disorder and interactions and give rise to a number of novel signatures. Solving the equations of motion for the interacting disordered system on the basis of a one-dimensional two-band tight-binding model the following phenomena are predicted: (i) the spatial extension of an initially locally excited electron-hole wave packet is much more pronounced if the many-particle interaction is taken into account, compared to the interaction-free case, and in contrast to the exponential temporal dynamics the dynamics of the interacting system becomes diffusive, (ii) two photocurrent pulses generated by coherent control with a certain delay time relax due to scattering at the disorder, but lead to one or two spontaneous current echoes at later times, (iii) pulsed optical excitation of a disordered semiconductor nanoring produces correlated electron-hole pair wave packets that execute a circular motion if a magnetic flux penetrates the ring, thus generating circularly polarized THz-radiation.

"Optical/THz properties of semiconductor quantum wells"

David Citrin
Georgia Tech

Abstract not available